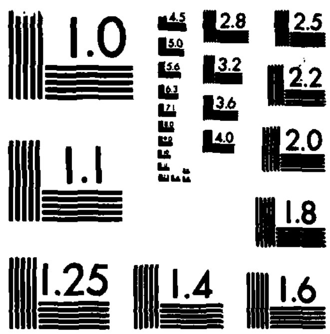
AD-A160 934 PROCEEDINGS OF A CONFERENCE ON A COMPREHENSIVE TECHNICAL REVIEW OF HUMAN (U) NAVAL AIR DEVELOPMENT CENTER WARMINSTER PA D K MCBRIDE ET AL 11 MAR 82 1/3

UNCLASSIFIED SBI-AD-F630 624 F/G 5/5 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

PHOTOGRAPH THIS SHEET

AD-A160 934

DTIC ACCESSION NUMBER

II

LEVEL

1

INVENTORY

ADF630 624 (2266TR)

DOCUMENT IDENTIFICATION

9-11 mar 1982

A

This document has been approved for public release and sale; its distribution is unlimited.

DISTRIBUTION STATEMENT

ACCESSION FOR		
NTIS	GRA&I	☒
DTIC	TAB	☐
UNANNOUNCED		☐
JUSTIFICATION	per ltr	
BY		
DISTRIBUTION /		
AVAILABILITY CODES		
DIST	AVAIL AND/OR SPECIAL	
A-1		

DISTRIBUTION STAMP

DTIC COPY INSPECTED

DTIC ELECTE OCT 16 1985 S E D

DATE ACCESSIONED

DATE RETURNED

85 09 24 099

DATE RECEIVED IN DTIC

REGISTERED OR CERTIFIED NO.

PHOTOGRAPH THIS SHEET AND RETURN TO DTIC-DDAC

DTIC FORM 70A DEC 83

DOCUMENT PROCESSING SHEET

PREVIOUS EDITION MAY BE USED UNTIL STOCK IS EXHAUSTED.

1

2266TR
adF630624

Design For Maintainers

Proceedings of

a Conference Hosted by the

NAVAL AIR DEVELOPMENT CENTER

Chairman:

LT Dennis K. McBride

9-11 March 1982

Holiday Inn Convention Center, Pensacola Beach, Florida

PROCEEDINGS,
HUMAN FACTORS
DESIGN FOR MAINTAINERS
CONFERENCE

A Comprehensive Technical Review of Human Factors Technology
in the Design-for-Maintainers

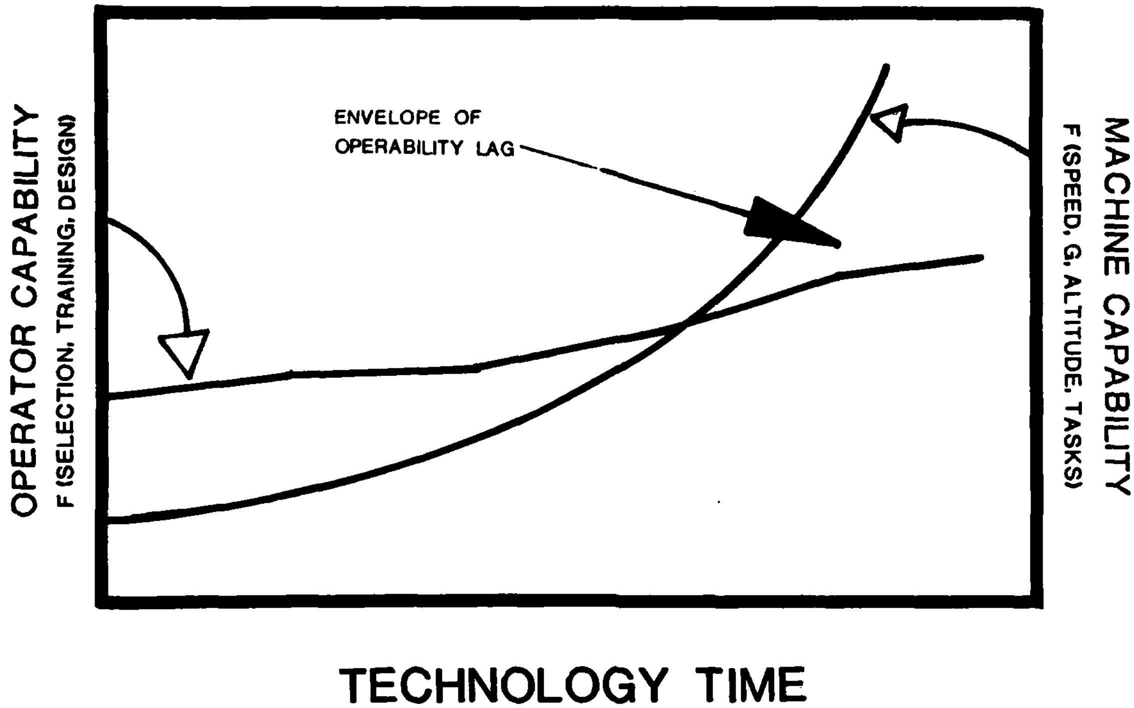
Edited by:

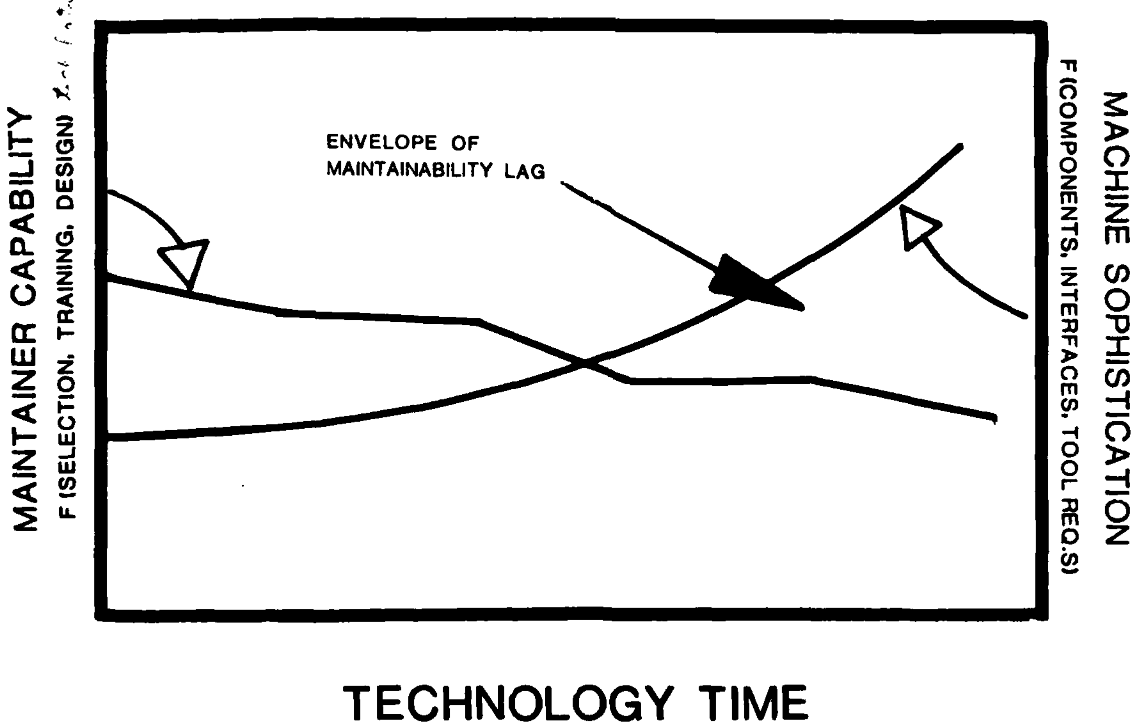
D. K. McBride, J. V. Lambert
L. Murray, and L. Hitchcock

9-11 March 1982

The Holiday Inn
Convention Center by the Sea
Pensacola Beach, Florida

PREFACE


OPERATOR CAPABILITY
F (SELECTION, TRAINING, DESIGN)
ENVELOPE OF
OPERABILITY LAG
MACHINE CAPABILITY
F (SPEED, G, ALTITUDE, TASKS)
TECHNOLOGY TIME


MAINTAINER CAPABILITY
F (SELECTION, TRAINING, DESIGN)
ENVELOPE OF
MAINTAINABILITY LAG
MACHINE SOPHISTICATION
F (COMPONENTS, INTERFACES, TOOL REQ.S)
TECHNOLOGY TIME

FOREWORD AND ACKNOWLEDGEMENTS

The preface does as well as perhaps any remarks in introducing these proceedings. The theoretical operability deficit (e.g., for aircraft) is modulable through the incorporation of such advances as cockpit engineering decision augmentation technology, task allocation methods, voice interactive technology, etc. What advances are we to rely on, however, for deflating the growing lag in maintainability? The reports contained here represent a compendium of current thinking on the matter. They were produced by a diverse body of subject matter experts, and they comprise quite an array of philosophies. The common denominator is, of course, the human factor.

Although this document is one of only a very few dedicated exclusively to human factors in maintenance, it is no doubt the most recent. The information, innovation, and more than anything, the enthusiasm, that were so vigorously and successfully exchanged at the conference will represent only the first such endeavor; the Department of Defense Human Factors Engineering Technical Advisory subGroup for Human Factors in Logistics (LOGSTAG) has eagerly sought to sponsor the symposium on a yearly basis.

The conference and this publication would not have been what they were without the tenacious dedication of several key players: Ms. Louida Murray, Ms. Laura Hitchcock, Dr. Joe Lambert, and Ms. Sharon Morgan. Their untiring capacity for work, exemplary professionalism, and enthusiastic support were truly inspirational.

The comments, opinions, and philosophies contained in or inferred from the reports that follow are not necessarily those of the U.S. Navy, nor of any of the respective sponsors, unless otherwise stated.

Dennis K. McBride, Ph.D.
LT, MSC, USNR
Manager, Design-for-Maintainers, and
Chairman, Design-for-Maintainers Conference, 1982

TABLE OF CONTENTS

A Human Factors Design-for-Maintainers Technology Development Program

Dennis K. McBride
Naval Air Development Center
Warminster, Pennsylvania

Joseph V. Lambert
Eagle Technology, Inc.
Warminster, Pennsylvania

The problem of maintaining airborne systems has grown considerably over the past two decades. With the increased size and ever-growing complexity of modern aviation weapon systems, estimates for maintaining them now range from 1/4 to 1/3 of the entire, yearly DOD budget[1]. Furthermore, it has been estimated that as many as 1/3 of all military personnel are detailed exclusively to maintenance and support functions. Apparently, however, traditional problem solutions have not worked. A typical Navy squadron today may, for example, have only about 50 percent of its aircraft available for full operational use. An analysis of the 3-M data on the F-14, to isolate one problem area, reveals (1) that because of excessive mean elapsed maintenance times (EMT), a $2.3 B excess inventory of F-14s is needed in order to maintain a prescribed, mission-capable force, and (2) that maintainer errors alone (e.g., diagnostic false alarms or maintenance-produced damage) account for a staggering share of unscheduled maintenance costs (Fuchs & Inaba, 1979). This means that an additional 1.23 maintainers are needed <u>per aircraft</u>, merely to recover from performance errors[1].

Clearly, when it comes to operational readiness, <u>reliability</u> is, and always has been a key issue (see, for example, Willoughby, 1981), but because of the acceleration in the subsystem complexities which characterize modern aircraft, even if overall system reliability could manage to sustain present day levels (or even improve, miraculously), measured <u>maintainability</u> would no doubt continue to decline. While such technological advances as Built-in-Test (BIT) and modularization certainly show promise, unfortunately, there is good reason to believe that early predictions for their success were quite probably overly optimistic (e.g., BIT reliability for the F-14 is, at best, disappointing). Polling of the participants at this symposium (over 376 man-years pooled experience) reflects this disappointment (Appendix A; McBride, 1982). BIT's perceived reliablity as a cure for diagnostic ills, is for this diverse body of symposiasts, at least, lukewarm. And its perceived future potential is only slightly better. Furthermore, forecasts for the availability (dwindling supply) and trainability (accelerating costs) of a future, qualified population of organizational-level maintainers are pessimistic.

The essence of maintainability is, of course, fast, safe, efficient repair; and at its heart are people-related variables--factors such as

diagnostic behavior, decision/cognitive complexities, reading comprehension, job aiding technology, accessibility, psychomotor coordination, anthropometric matchups, transfer of training, man-to-machine information transfer, and systematization. These human factors must be comprehensively and systematically examined, and the performance-based discoveries which their research provides must be elegantly intermeshed as design criteria, standards, and specifications. Design-for-Maintainers (DFM) is NAVAIRSYSCOM's (340-F) multidisciplined technology development program, aimed specifically at this most crucial manpower/readiness problem. The R & D effort is performed by the Naval Air Development Center (NADC Human Factors Technology Development, Aircraft and Crew Systems Technology Development Directorate, Warminster, Pennsylvania) under Program Elements 62757N and 63710N. (The Office of Naval Research sponsors a related and coordinated effort.)

Following is what must be only a superficial overview of some of the philosophical issues which underlie the steering of DFM technology development. In order, the following topics are addressed: (1) Reliability and Maintainability; (2) The Human as a Factor; and, as an introduction to the reports following, a brief introduction to (3) Design-for-Maintainers.

Reliability and Maintainability

Blanchard and Lowery (1969), tell us that maintainability (M)[1], as an "accredited" engineering discipline, evolved as a product of the many reliability (R) engineering efforts of the 1940s and 1950s. Perhaps as significant as any M-related historical landmark, the Pentagon, in 1954, formally ($) acknowledged and adopted M as the curative counterpart to R, the preventive. Since that time, both R and M have experienced the ad hoc attention so typically devoted to adoptees, the "Oh yeh, let's not overlook R & M" policy. Although R and M comprise (as subsumed under logistics) something called, perhaps simplistically, but at least singularly, "Systems Availability Technology," it is a curious but common perception that these disciplines have evolved as mutual adversaries. Competition for resources ($) no doubt shares some responsibility for their evolutionary branching; but for whatever reasons, "Big R/Little M," "Big R/Important M," etc., although aimed at precisely the same goal--availability, and exploiting precisely the same approach--system reliability (machine, man), continue to regard the other as threat.

Regardless, one serious question for both R and M philosophers has to do with what seems somehow counterintuitive to a surprisingly large camp. That is, although component/subsystem reliability has continued to increase over recent years, system reliability has continued to dwindle. The solution is, of course, that the number of components which comprise modern aircraft has also increased over the years, and since overall system reliability is a product of the combined "subreliabilities," availability has declined. To risk insulting the sophisticated reader, take the following example. Suppose the mean reliability for essential components for a particular system (i.e., a defect means aircraft is grounded) experiences a dramatic, linear growth from say .9 to .99 over some ten-year period. For the same period, let's say that

---

[1] M = concept/discipline, $\overline{M}$ = measure of M

the number of assemblies, parts, etc.--the components which constitute the aircraft--and the number of component interfaces also increase linearly, by a theoretical factor of .1, so that the "average" aircraft at the end of our 10-year study window has 10 percent more components (and even more interfaces) than its "average" predecessor. Exercising a simple cumulative binomial model of failure prediction shows that there is not an increase, but a decrease in aircraft availability. That is, the probability that no parts will be portrayed as faulty on some theoretical, time-frozen snapshot of aircraft availability has actually decreased. Furthermore, these hypothetical figures represent rather conservative depictions of trend; in reality, component reliabilty has obeyed an increasing, but negatively-accelerated growth curve, and component proliferation is more typically positively accelerated (or sigmoidal). This all means, of course, that technology must drive component reliability upwards by a very immodest exponential factor in order to maintain constancy in system availability. History shows clearly that this requisite cannot be met.

For it is written, then, that systems fail. The issue, therefore, becomes one of repair. And it is the repairman's reliability--the probability that his performance error will not render a system unavailable--that now becomes a central consideration. So, *how much variance in TURNAROUND-TIME do maintainer (vis a vis, supply) variables ACTUALLY account for?* The answer is not clear, largely because of the question of the immediacy of maintainer involvement in many of the multitudinous facets of maintenance activity. Not surprisingly, however, this lack of clarity does not yield a paucity of answers. The disappointingly few, though highly significant, contributions in the literature (Blanchard & Lowery, 1969; Crawford & Altman, 1972; Rigney, Cremer, & Towne, 1965; Topmiller, 1964; see Hsu & Theisen, these Proceedings for a review) suggest strongly that the human interface is in fact key. Fuchs and Inaba (1979), for example, have shown that maintainer errors can be reduced in simulation by as much as 97 percent with appropriate manipulations of design. Furthermore, M practitioners do not point smartly to the numbers of technical publications devoted to HFM--there are only a few. The man-hours invested, however, are staggering; and a quick look at the results of the opinion poll (Appendix A; McBride, 1982) leave no doubt that those who worry about M problems, scientist and maintainer alike, share a mind: variance contributed by the human interface is legion.

On the other hand, many operational maintainers and officers perceive the above account as a tenuous indictment of technician skill level, and instead, invoke supply (viz., parts availability) as the chief, if not the only nemisis of efficient turnaround. There are literally scores of supply-related management problems for which human factors technology has been, and should be, providing solutions. As one real example of this potential, voice technology has shown considerable promise for the remediation of catalog/inventory/distribution/disposal problems. For present purposes, however, attention is devoted to the design of equipment and its interaction with human variables.

The Human as a Factor

Maintainer reliability is underpinned, of course, by a number of factors, the first of which, could be characterized as demographic or personnel. In the Navy, for example, there is a generally reliable, three-way classification

of first-tour Navy maintainers. Comprising the first category are those who need a job tomorrow; they impulsively apply for enlistment, pass the necessary screening exercises, and by a "thought-out" Navy selection process, they are assigned to a track which, in many cases, will ultimately become a severely truncated career. These individuals have an excessive desertion rate, and their performance is generally well below average--observations interpretable as motivational problems. The second category, those who are career-(read security) minded, typically come from disadvantaged socioeconomic backgrounds and are typically poor in such abilities as reading, communication, comprehension, etc. The third grouping, fortunately, represents the largest population (>60%) of entering Navy maintainers. They are bright, eager to learn, suffer fewer motivational problems, and perform exceptionally well. Unfortunately, over 90 percent of these maintainers leave for better pay/conditions after their first tour. The problem for the Navy, of course, is the resulting negative relationship between time-in-service (and thus, assigned responsibility level) and basic skill level. Of those who do not choose to make the Navy a career, the probability that a maintainer will terminate his Navy service increases with measured ability level and experience. In other words, those who cost most to train and do the best job don't stay.

The second conglomeration of human issues which help predict maintainer performance can be classified as training and educational factors. The Navy has an elaborate assignment scheme which factors in such variables as recruiting commitments, PCS costs, school quotas, etc. for determining training and specialization tracks for sailors. Theory, applications, and on-site training are intermeshed according to any number of variables, and performance is evaluated continually. Scores of arguments have been and can be raised with regard to the effectiveness of current training methodology (e.g., see sections in these Proceedings) but one limiting factor surely underwrites the ultimate impact of all the "mega dollars" of training and simulator expenditures. That factor, as outlined in the previous paragraph, asserts that the effectiveness of any training or selection innovation is no better than the a posteriori likelihood that selectees and trainees continue in service. Unfortunately, psychologists have long known that those who profit most from traditional training are not universally those who begin training with the lowest skill levels.

Furthermore, as the sophistication of aircraft has grown, the nature of the underlying variables which govern maintainer performance has also changed. Figure 1 illustrates the point. Forty years ago, it was conceivable (and imminently practicable with the draft) to recruit (select) a body of maintainers, who with a modicum of "repairman" experience and a minimum of training, comprised a qualified population of operational maintainers. As aircraft complexity increased, however, more and more training was found to be necessary, so that in the 1980s, training expenditures (including simulator technology) for maintenance and logistics have, by necessity, soared.

Summarized rather simplistically, when the effectiveness of personnel and training methodologies begin to approach their technological end points--whether because of accelerating system sophistication, technician skill deficits, or whatever--it becomes painfully clear that in many ways it is less expensive to manipulate the design of equipment than to "manipulate the design of human capability or its expression."

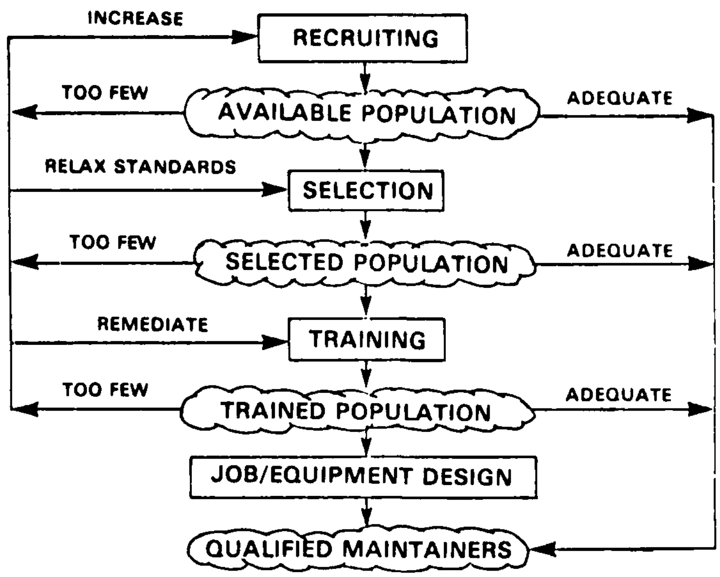


Figure 1. Schematic portrayal of the impact of increased aircraft sophistication on the variables underlying maintainer performance.

Design-for-Maintainers

DFM is based philosophically on the tenets outlined above. Presented simply, the program can be characterized as in Figure 2. The ultimate concern, of course, is the useful output provided now and in the future by DFM. This output comes in two mutually interactive varieties: (1) engineering solutions to existing problems, as for example, the F-14 ECP depicted in Figure 3, and (2) technological advances for the prevention of future problems. The methodology which provides these products is common to both, and it involves, first of all, the application of state of the art HFM principles toward well-recognized, M problem targets. This "application" may take several approaches. For example, a known, incorporated design feature or change may have been driven, let's say, by the need for greater accessibility to a particular avionics component. Aviation 3-M data, or perhaps squadron reports, are analyzed after the fact to determine the $\bar{M}$ consequences of the engineering feature. The application may, however, not be "after-the-fact," but instead, it might be an attempt to verify in a controlled fleet setting (e.g., NAMTRADET) or well-controlled laboratory, the predicted impact of a single or set of HFM features on $\bar{M}$.

The critical task of validation then begins. Here, the effectiveness of the design/redesign inputs is scrutinized; the nonproductive elements are discarded or rethought, and the productive ones are retained. A factor-analytic-like approach then partitions the valid design enhancements into such traditional categories as accessibility, diagnostic complexity, biodynamic stress, or it suggests new ones. As the validation process continues, the methodology is expanded to other components, subsystems, and systems, where validation and update continue to support this progression.

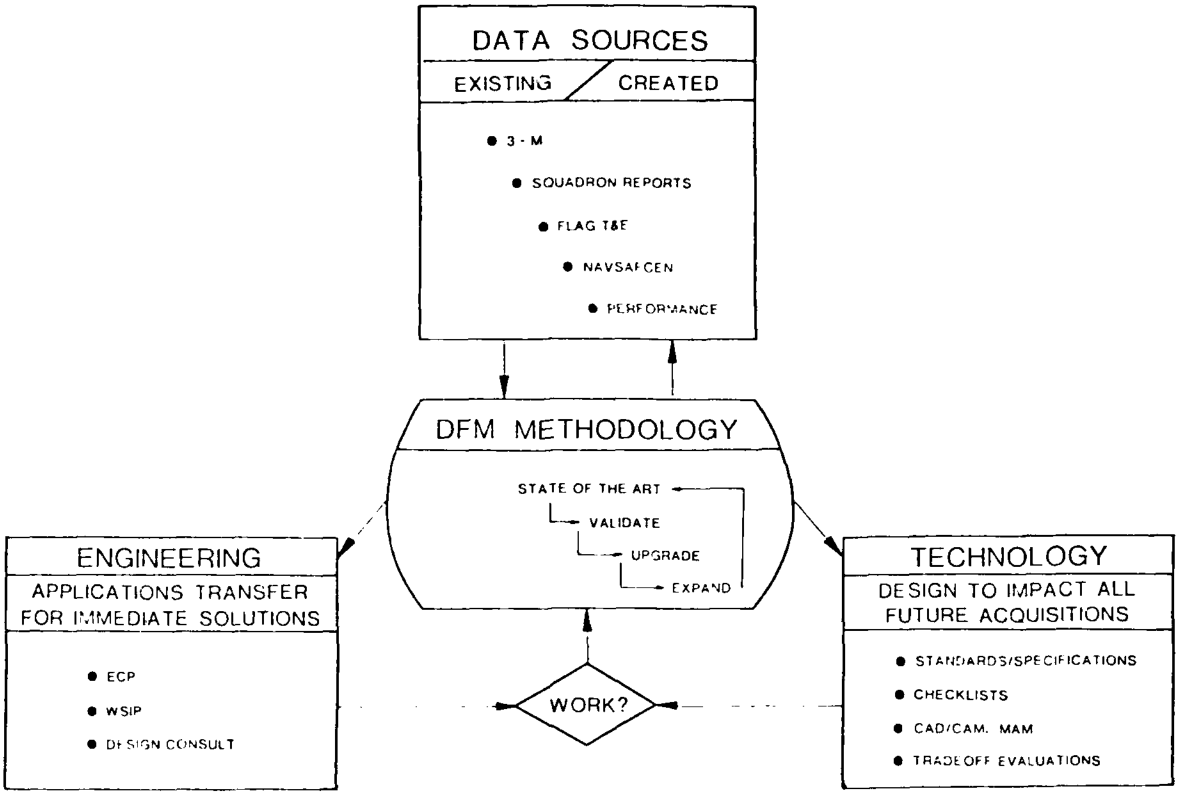


Figure 2. Outline of Design-for-Maintainers program.

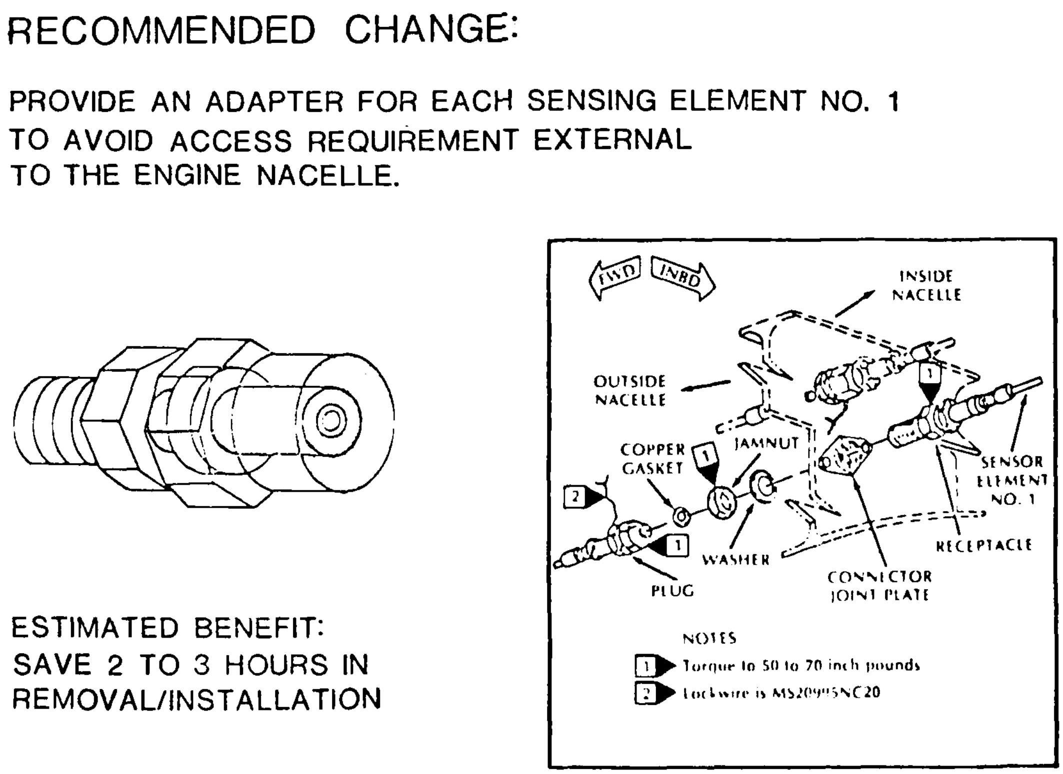


Figure 3. One example of an ECP which would impact maintainer efficiency.

Table 1

SELECTED HFM MAJOR INSTALLATION RECOMMENDATIONS

COMPONENT	RECOMMENDATIONS	INCORPORATED?	ΔM̄?
Forward Reaction Control Nozzle	Reduced number of fasteners	Yes	
	Standardize bolt length	No (Different thickness)	
R. H. Console	Move panels aft to allow direct removal of electrical panel	Yes	
FWD Avionic Bay Door	Provide head clearance	No (Gooseneck hinge size restrictions)	
INT Lights Controller	Change mounting bolts to hex head for tool access	Yes	
Kickshields	Redesign mounting brackets for ease of removal	No (Sufficient bending)	
Fuel Probe	Change grounding screw to captive screw	Yes	
Pitch Servo	Redesign actuator for reducing replacement/rigging procedures	Yes	
Door 10	Add lanyard to prevent straining ALR-67 antenna cables	Yes	
Formation Lights	Splice at moldline when replacing	Yes	
Swingbolt/ Unserside	Provide spring mechanism to retain swingbolt out of removal envelope	Yes	
Options Display Unit	Add handle for ease of removal	In-work	
Crewstation Electrical Wiring	Use structural hat section as conduit to eliminate clamps/ exposed wiring in cockpit	In-work	
Daily Access Door	Hinge upward or to side for better access to wheel well	No (Door is in view when opened)	
JPTL	Utilize slide mounting	No (Side door removal)	
Autostab Pitch Actuator	Redesign to simplify installation procedure	Yes	
Throttle Quadrant	Redesign access to throttle stops for ease of rigging	Yes	
AFT Avionic Bay Doors	Hinge doors upward	No (Severe weight penalty)	

An example of an ongoing effort might serve well here. When the Navy's F-18 became a blueprint reality, HFM engineers made, literally, hundreds of inputs aimed at improving the aircraft's maintainability. Whereas the F-14 had shown an MMH/FH figure in excess of 40 (i.e., a man-week effort required to prepare the aircraft for the next 1 hour of flight!), these F-18 design features (Table 1) were intended to bring that figure down to around 11, a much more tolerable maintenance burden. With the establishment of the first F-18 squadron, the success of those state of the art, engineerng features can now be tracked via a systematic examination of aviation 3-M data. And the analysis of these successes and unproductive solutions underlies the development of ongoing HFM technology. If, for example, certain design features consistently induce diagnostic false alarms/false removals, and others lead more typically, say, to equipment damage errors, then standards, specifications, checklists, even CAD/CAM interactive models can be generated to decrease the prevalence of their incorporation into the design of future systems. Such associations are being borne-out currently by DFM. These preventive measures--technological design aids--have proved in the past, and can continue, to save millions in maintenance man-hours and dollars.

Currently, and as many of the following reports show, DFM methodology is exploiting several data bases, but it is deliberately concentrating on a relatively small cross section of platforms. The F-14, because of its recognized M problem, its mature-yet-relatively-new status as a fighter aircraft, the vast number of ECPs associated, and its ample maintenance data reserve, represents quite a target for HF attention. Other aircraft are also prime attractions: the EC-130 (unique O-level maintenance scheme), the SH-2F (a rotary wing), the F-18, and the F-4. Plans are in work for the VT-X. The data sources also vary from 3-M, to FLAG T&E, squadron reports, structured interview, structured maintenance activity analysis, and on to NAMTRADET performance records.

The program is solution-driven. Yet, neither engineering curatives, nor technological preventives will represent a M panacea. The effectiveness of the approach is no better than the extent to which the user community--the PMAs, advanced concepts technologists, safety engineers, class desks, R & M engineers, operational maintainers, and squadron commanders--are actually intermeshed as active DFM subscribers. Transitional funding and sponsorship, therefore, must be two-dimensional: (1) DFM has in fact succeeded in establishing a relatively secure 6.1 (with ONR), 6.2, and now 6.3 transitional base. Growth on this dimension must be invigorated, however, with (2) an even more convincing and sustaining growth on the axis of "user acceptance." DFM is beginning to make this claim.

References

Blanchard, B.S. & Lowery, E.E. Maintainability principles and practices. New York: McGraw-Hill, 1969.

Crawford, B. M. & Altman, J. W. Designing for maintainability. In H.P. Van Cott and R. G. Kinkade (Eds.), Human engineering guide to equipment design. Washington, D.C.: U.S. Government Printing Office, 1972.

Fuchs, F. & Inaba, K. Design for the maintainer (Report No. NADC-79218-60). Warminster, PA: Naval Air Development Center, 1979.

McBride, D. K. An initial survey of human factors specialists to determine the perceived relative importances of several maintainability parameters (Human Factors Technical Memorandum No. 6021-1982-05). Warminster, PA: Naval Air Development Center, August 1982.

Rigney, J. W., Cremer, R. H., & Towne, D. M. The design of electronic equipment for ease of maintenance: current engineering design practices. TR-41, August 1965.

Topmiller, D. A. A factor analytic approach to human engineering analysis and prediction of system maintainability (AMRL-TR-64-115). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory, December 1964.

Willoughby, W. $\bar{R}$ quality. Military Science & Technology, 1981, 1, 28-32.

A Current Application of Design-for-Maintainers (DFM) Technology

Frank H. Fuchs

XYZYX Information Corporation
Canoga Park, California

An application of DFM technology is taking place right now in the city of Detroit. We have there a nonmilitary project involving maintenance on a bus. The bus in question is the GMC RTS II (Figure 1). The RTS II became operational in 1976 and is now in use in nearly every major city in the country.

In the project described here, DFM technology covers the following: information packages for use by maintenance personnel, solutions to problems posed by inadequate system design, inappropriate support equipment, counterproductive maintenance practices, and measurement of bus fleet performance reflecting maintenance effectiveness.

Our mission in Detroit is to help the Department of Transportation improve the availability of the RTS II through more efficient maintenance. Our original strategy was to drive down the mechanic error rate by means of Job Performance Aids (JPAs). However, as we moved into the work environment, we discovered other problems that also needed attention. Some of those problems are described in this report.

The project referred to covered three systems on the RTS II. In this particular account, we will concentrate on only one of them: the Heating and Air Conditioning System. First, we will look at the system in question; this will provide a context for the materials to follow. Next, we will see some samples of the JPAs and other information products delivered. We will then examine some maintenance problems caused by both the system designer and the maintainers themselves. We will describe our experiences in trying to implement our program. Finally, we will explain our approach to program evaluation.

Introduction to H&A/C System

Figure 2 illustrates a top-level view of the Heating and Air Conditioning System. It is comprised of four subsystems, namely:

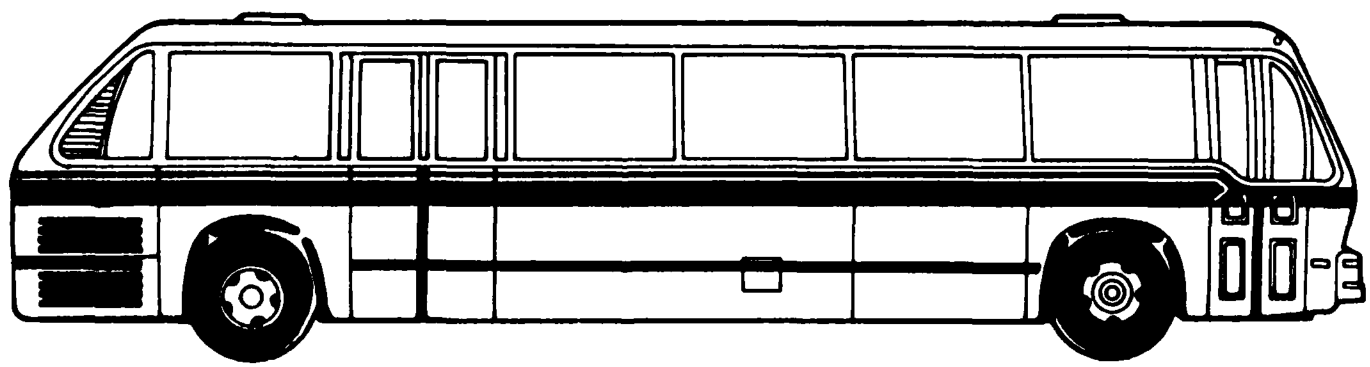


Figure 1. GMC RTS II Coach.

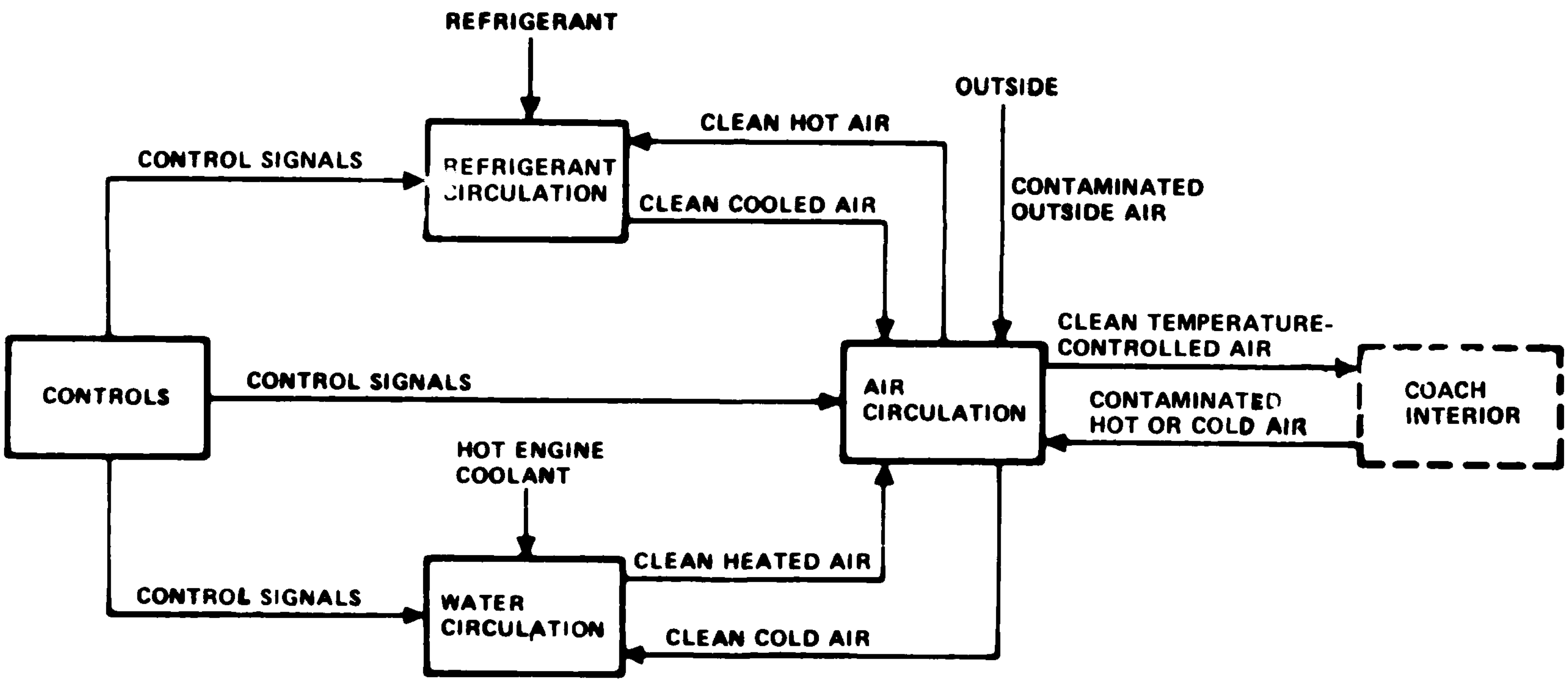


Figure 2. Heating and air conditioning system.

- Refrigerant circulation
- Water circulation
- Air circulation
- Controls

In certain ways, each subsystem is similar to its counterpart on other buses. Many of the components are identical, as are individual functions. What makes this system unique is that, for the first time, the functions of heating and cooling are brought together as a single system rather than two related systems. Another unique feature is the control subsystem. Mode selection is accomplished by thermostats sensitive to external air temperature. As we will see later, this feature is not necessarily beneficial to the mechanic.

Views of the respective subsystems as shown in Figures 3, 4, 5, and 6 are meant to show that the various components are in fact familiar to the maintenance community. That is a valuable characteristic in any new system. Another point of importance to the mechanic is component location. Here again, the designer did a good job. Physical access is not a big problem on this system.

Information Products Provided

Now that we have been introduced to the system itself, we are ready to see the first element of assistance given to the mechanics through our program--the information products. Chief among these products are the JPAs (Figure 7).

The list of JPAs reflects the entire scope of maintenance jobs applicable to the system. Most of the jobs entail component replacement and service-related actions at the component level. A small number of jobs, such as troubleshoot and check, apply at the system and subsystem levels. This distribution is typical of most systems.

Figures 8 and 9 represent sample pages from two JPAs and are shown in order to convey the flavor of the information involved. One illustrates a replacement job, the other, check and service. Note the following features of Figure 8:

- Job location and hardware appearance shown pictorially
- Numbered arrows marking each point to be touched
- Action statements carrying those same numbers
- Short, simple statements

Figure 9 features include:

- Specific criteria where a decision must be made
- Clear routing out of decision point

All JPAs are formatted in this manner.

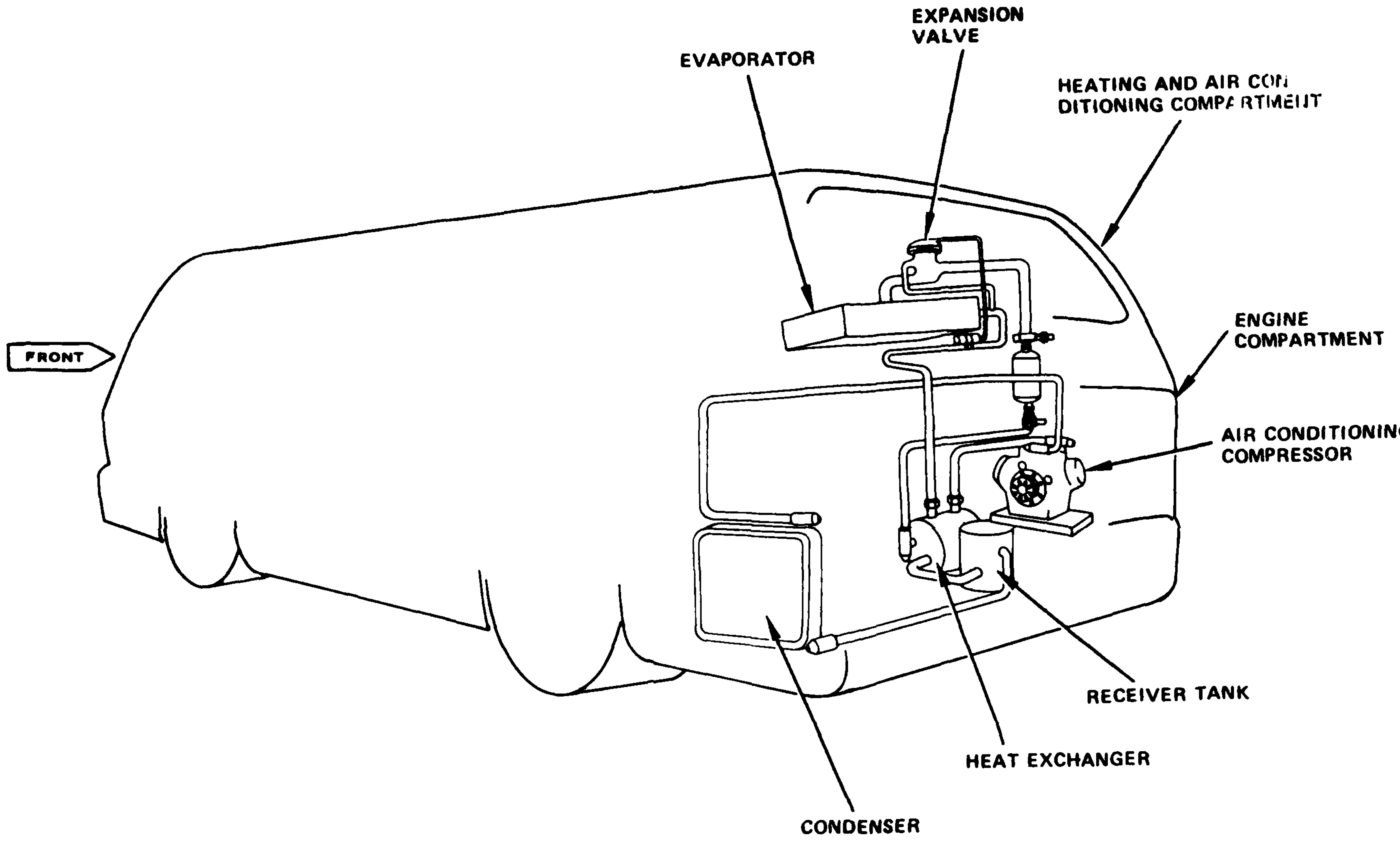


Figure 3. Refrigerant circulation subsystem.

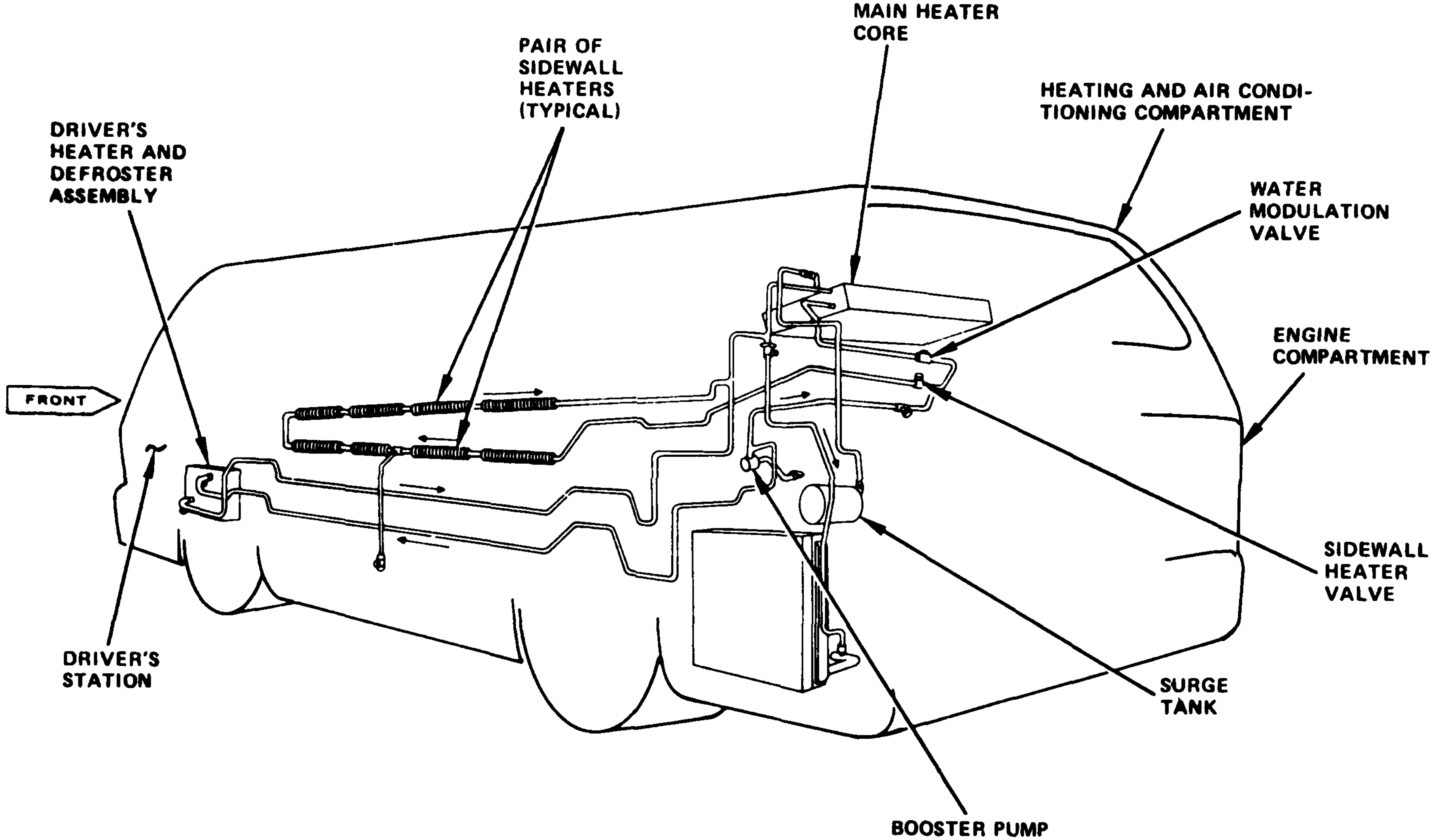


Figure 4. Water circulation subsystem.

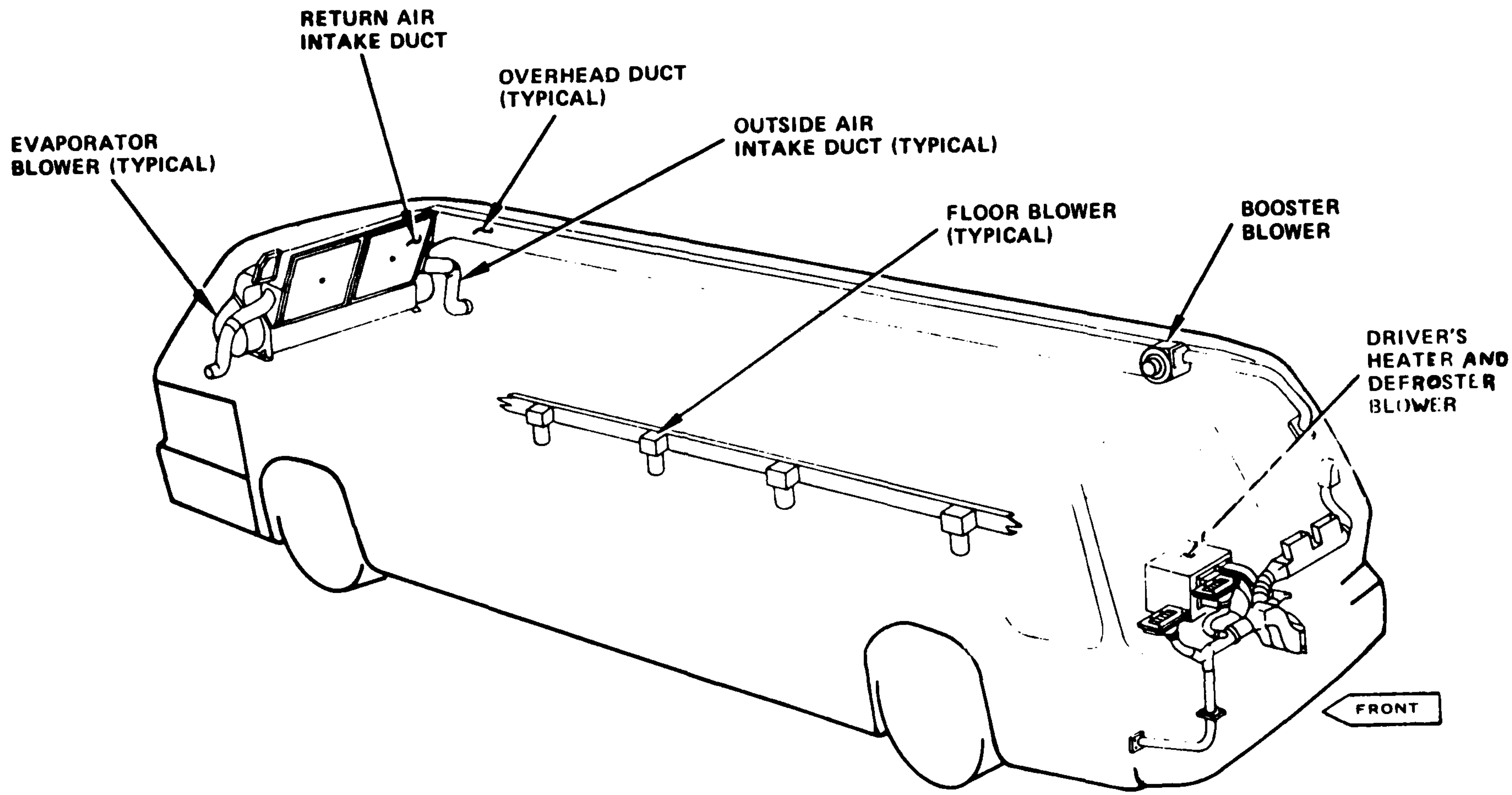


Figure 5. Air circulation subsystem.

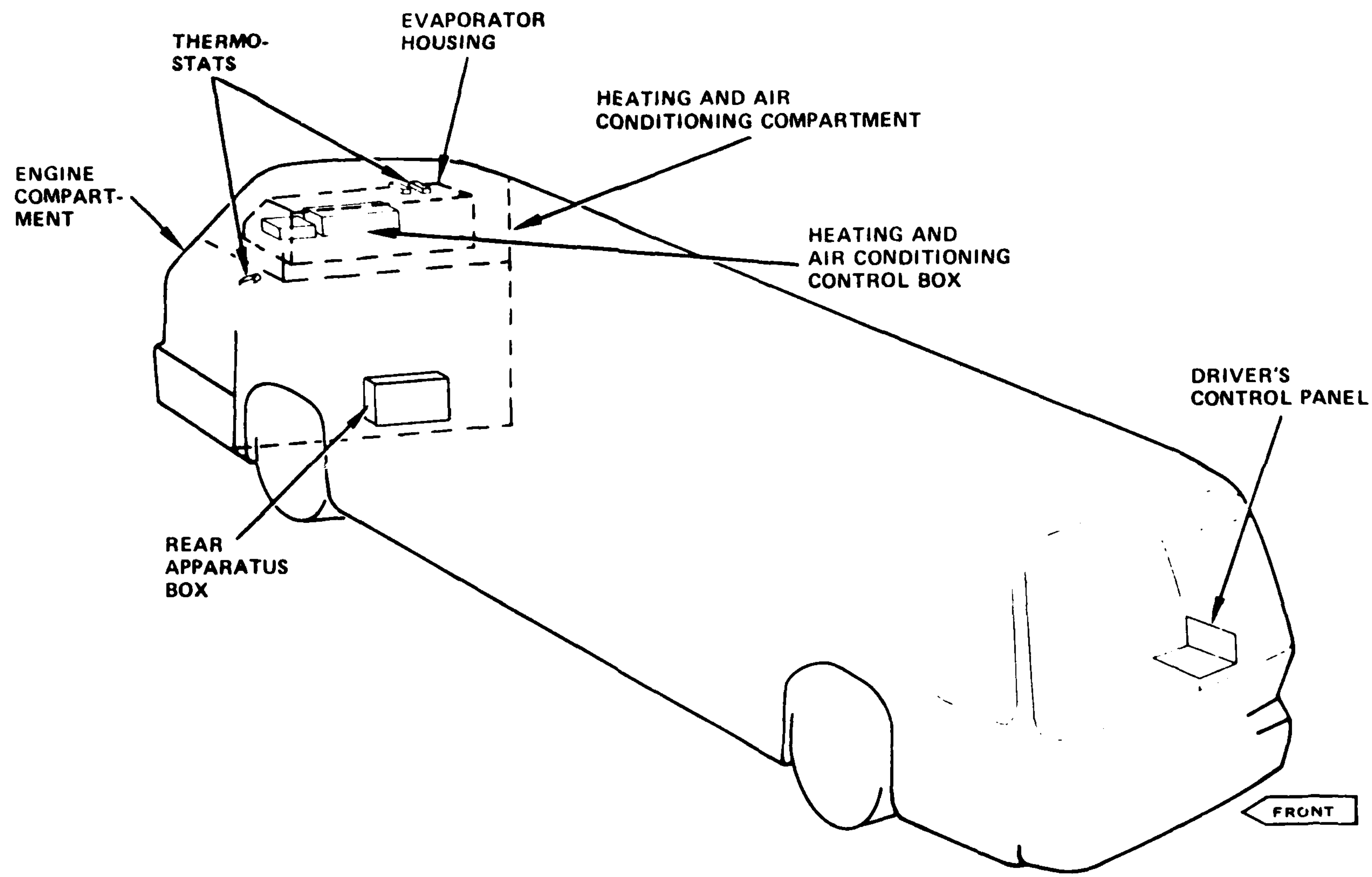


Figure 6. Control subsystem.

1. Troubleshoot Heating and Air Conditioning System
2. Check and Service Refrigerant System
3. Check and Service A/C Compressor
4. Service Heating Water System
5. Replace Toggle Switches, Circuit Breakers, and Relays
6. Replace Return Air Shutter and Shutter Air Cylinder
7. Replace Return Air Thermostats
8. Service Supply Air Filter
9. Replace Heating and A/C Control Box Components
10. Replace Hi-Lo Pressure Switch
11. Replace Blower Motor Relay Switch
12. Replace Hi-Speed Blower Motor Resistor Strips
13. Replace Fluid Drive Fan Override Solenoid
14. Replace A/C Oil Pressure Switch
15. Replace Blower Interlock Switch
16. Replace Booster Pump
17. Replace Perry Water Filter
18. Replace Water Modulation Valve
19. Replace Sidewall Heater Valve
20. Replace Check Valves
21. Replace Driver's Heater Components
22. Replace Booster Blower Motor
23. Replace Floor Blower Motor
24. Replace Return Air Filters
25. Replace Intake Air Filters
26. Replace Evaporator Blower Motor and Fan Wheel Assembly
27. Replace A/C Compressor and Components
28. Replace Filter-Drier and Valves
29. Replace Refrigerant Receiver Tank
30. Replace Refrigerant Heat Exchanger
31. Clean Condenser Coil
32. Replace Condenser
33. Clean Evaporator Coil
34. Replace Heater Core and Evaporator Assembly
35. Replace Refrigerant Expansion Valve

Figure 7. RTS-II heating and air conditioning system JPAs.

REPLACE BOOSTER PUMP

<u>Remove Booster Pump</u> (continued)

8. Remove vortex screen (4) from inlet hose (3). See if there is damage on screen.

In the following step, hold BOOSTER PUMP while removing flange bolts (1).

9. Remove four flange bolts (1) from pump clamp (2).

10. Remove BOOSTER PUMP from coach.

END OF ACTIVITY

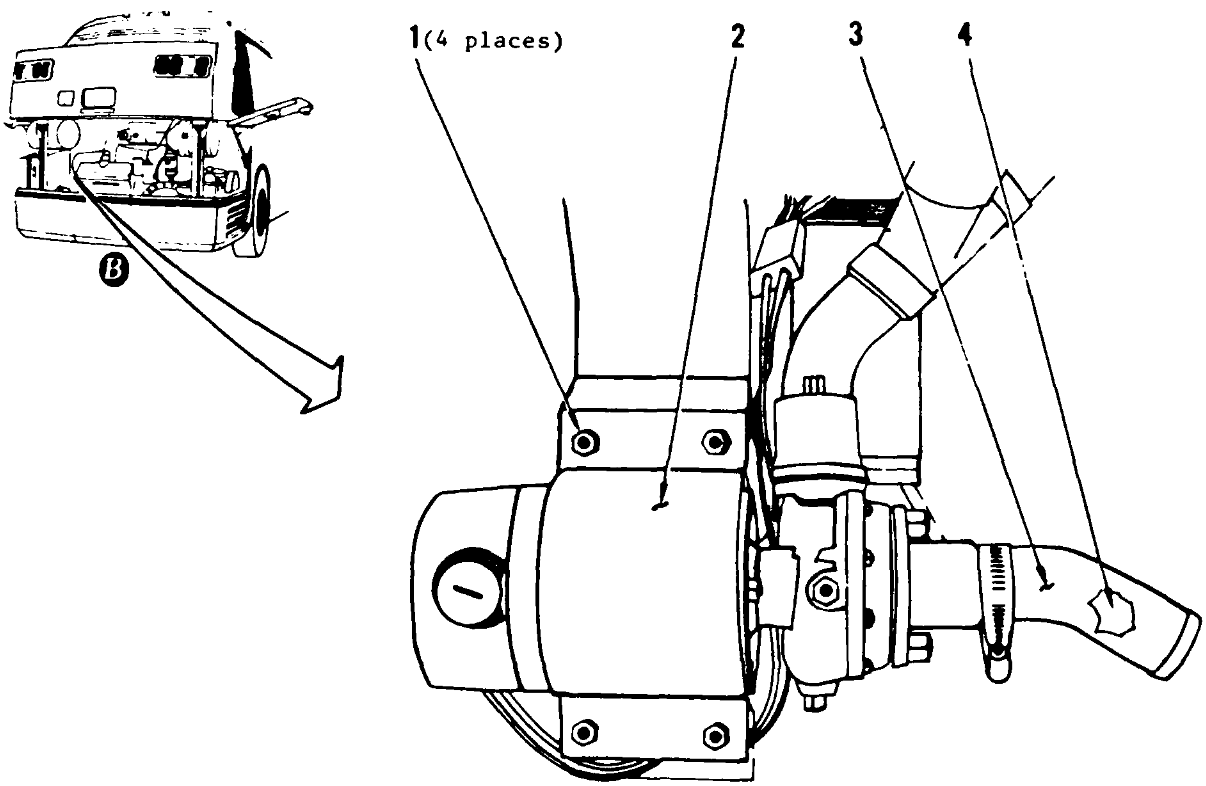


Figure 8. Sample JPA.

Check For Air In System (continued)

To obtain proper temperature reading, thermometer or sensor must be fastened to condenser line with thermo-mastic tape.

9. Place thermometer on condenser line (1). Wrap with tape. Wait ten minutes, then note temperature.

10. Using two temperature readings, determine average temperature.

11. Note reading on high pressure gauge (2).

12. See if reading on high pressure gauge (2) is within three psig of pressure on Temperature Relationship Table, page 9.

    If reading is within three psi of value on table, go to Step 17, Page 9.

    If reading is not within three psig of pressure on table, continue.

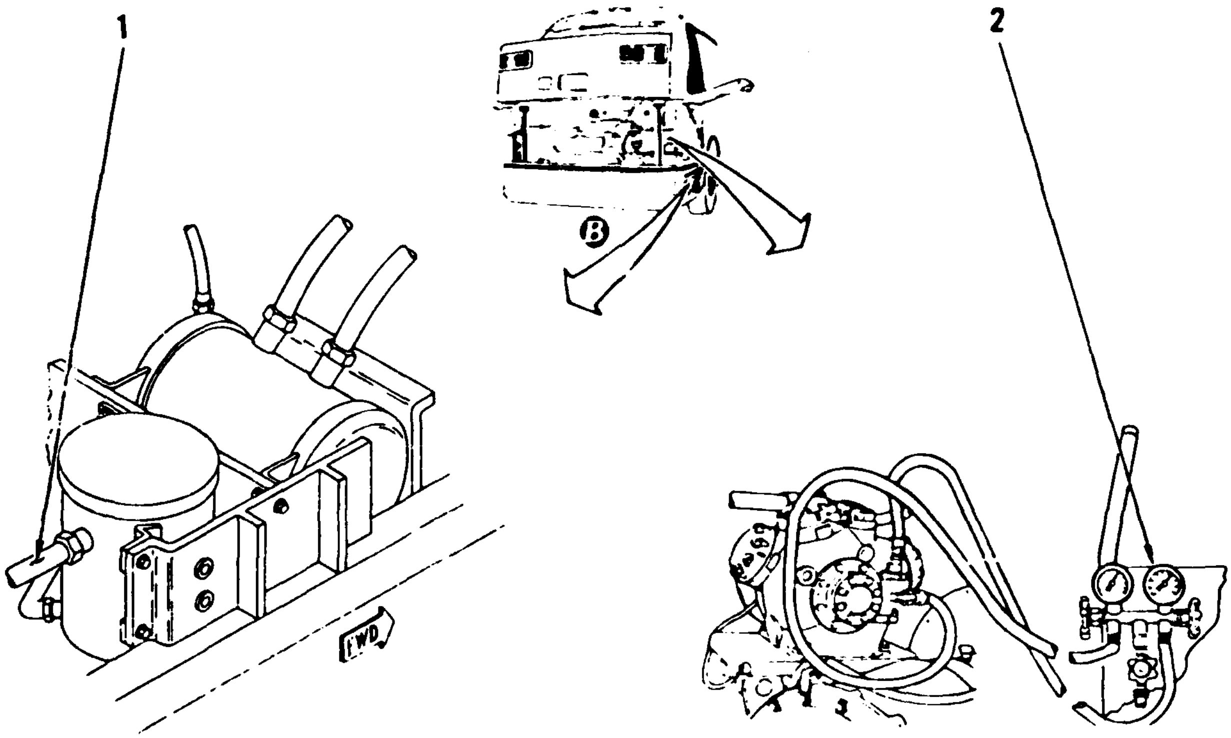


Figure 9. Sample JPA.

Certain tasks are common to several jobs. In order to control against repetition, such tasks are best covered outside the JPAs and then simply referred to as the need arises. In this project, the document used to do that is called a Skill Aid. Eleven Skill Aids were required for the Heating and Air Conditioning System (see Table 1).

Strictly speaking, the term "skill" may not be the most accurate one to use. We frequently think of skill in connection with sensorimotor faculties. But, in maintenance, those kinds of abilities are seldom needed. Maintenance jobs are much more likely to be driven by the need for information.

Figure 10 is a sample page from a Skill Aid. The presentation techniques employed are similar to those used in JPAs. The halide torch, by the way, is a device used to check for leaks in refrigerant lines. When the flame comes into contact with leaking Freon, the flame changes color.

The final information product to be exhibited (Figure 11) is the system explanation. The purpose of a system explanation is to give the mechanic an understanding of how the parts of a system work together to produce the required outputs. Such information is vital to effective troubleshooting.

The page shown in Figure 11 is from the first section of the explanation. The picture will be recognized as one illustrated earlier. The first section is expressed in very simple terms. The intent being merely to establish a foundation for the detailed passages that follow. The system explanation, like all the other information products developed for the project, makes use of well-founded principles of presentation and learning.

Maintenance Problems

The Heating and Air Conditioning system on this particular model/series produced a number of interesting maintenance problems. Some were caused by the system designer, others by the maintainer. It is sometimes hard to tell where one stops and the other begins.

Refrigerant leaks are a case in point. This bus has had a persistent problem with leaks. Some experts say it was due primarily to vibration. Others say the chief cause was overpressurization. We don't know which side is right. We do know, however, that the leaks have been there, and that the maintainers were not, at first, dealing with them effectively.

Leaks, by the way, are a triple-threat problem in refrigeration systems. First, of course, they allow the Freon to escape gradually, thus reducing the cooling power of the system. Second, they permit the entry of air bearing moisture which combines with the Freon, hydrochloric acid is formed, which causes internal corrosion, and further aggravation of the original leakage problem. Finally, the leaks make necessary a higher frequency of corrective actions which happen to be very time-consuming in nature.

With these facts in mind, we can now look at two maintenance practices that were clearly counterproductive. The first practice has to do with cleaning the outside of the bus. Implicated are both cleaning personnel and

Table 1

RTS-II Heating and Air Conditioning System Skill Aids

SKILL	PHYSICAL	PERCEPTUAL	MENTAL
1. How to Use Halide Torch		X	
2. How to Perform Quick Warmup			X
3. How to Determine and Set Heating & Air Conditioning Mode			X
4. How to Use Evacuation Station			X
5. How to Use Refrigerant Gauge Set			X
6. How to Use Freon Tank			X
7. How to Use Burroughs Belt Tension Gauge	X		
8. How to Solder Copper Tubing	X		
9. How to Repair Electrical Wiring			X
10. How to Use Test Light and Volt-Ohmmeter			X
11. How to Use Wiring Diagrams and Wire Codes			X

Introduction

The halide torch, also called "sniffer", is used to detect and locate leaks in the refrigerant system. The torch consists of the following parts:

- o fuel tank (6)
- o valve (5)
- o burner (2) with copper plate (4)
- o pick-up hose (1)

The torch may burn propane, alcohol or acetylene.

When the valve (5) is opened, fuel flows from the tank into the burner (2). The fuel should be ignited within a few seconds of opening the valve. Otherwise too much fuel escapes into the surrounding air. Too much fuel in and around the burner can result in a burned hand when the fuel is ignited, or even cause a fire or explosion hazard. Once the flame (3) is burning, the valve is used to adjust the size of the flame.

The heat generated by the flame draws air through the pick-up hose (1) into the burner. The color of the flame indicates the presence or absence of Freon gas in the air. Therefore, the color of the flame should be observed when air <u>without</u> Freon is drawn into the burner. This "normal" color depends on the type and quality of the fuel being burned.

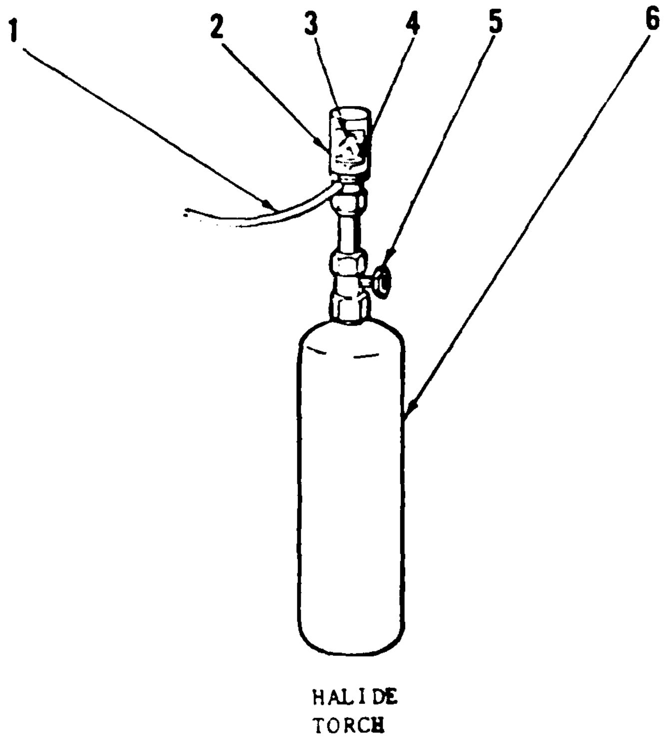
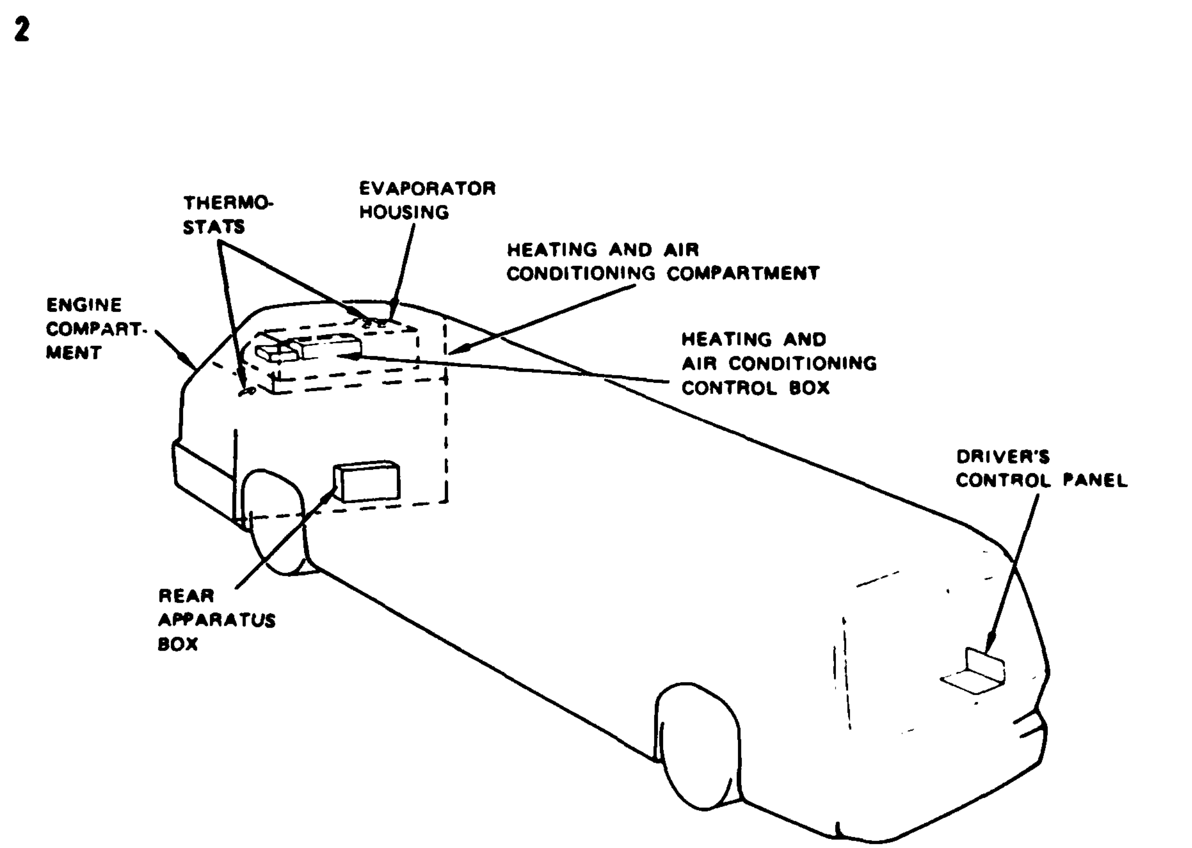


Figure 10. Sample page from a skill aid.



CONTROL SUBSYSTEM

The control subsystem uses pneumatic and electrical devices such as valves, solenoids and switches. Control "decisions" are made by the thermostats.

Many of the automatic control components are located in the heating and air conditioning control box that is mounted on the rear of the evaporator housing in the heating and air conditioning compartment.

Manual controls are located on the driver's control panel. Key electrical control components are located in the rear apparatus box in the engine compartment and in the evaporator housing.

Figure 11. System explanation.

the system designer. The designer led off by placing the refrigerant condenser in the engine compartment, right beside the radiator. Remember now, that the radiator has beside it, a fan that pulls outside air in through the radiator for the purpose of cooling the engine (Figure 12).

In this case, the fan acts like a vacuum cleaner. Each day, dirt and debris are drawn in from the street and deposited on the condenser fins. The initial result is to restrict the flow of air through the condenser, thus reducing the condenser's ability to transfer heat from the refrigerant to the outside air. At this point, cleaning personnel take over. In their zeal to get the condenser back to normal, they use the strongest measure available to them: steam cleaning. The steam is effective in cleaning the condenser fins. The problem is, it is also effective in overheating the refrigerant lines. When refrigerant is overheated, it builds up pressure rapidly. For example, refrigerant at 120 degrees Fahrenheit exerts 160 pounds of pressure. At 135 degrees, the pressure increases to 200 pounds. By 150 degrees, the pressure escalates to 800 pounds. The refrigerant lines, meanwhile, are designed for 250 pounds of pressure. Thus, the high pressures, created by the excessive heat of the steam, place a severe strain on the lines, greatly increasing the chances of further leaking. Fortunately, the practice of steam cleaning around the refrigerant lines was stopped after attention was drawn to its bad effects.

The second example of a counterproductive maintenance practice involves support equipment (Figure 13). Here again, the refrigerant lines play an important role. Leaks must be dealt with as follows:

1. Empty system of refrigerant
2. Repair leaks by soldering
3. Evacuate system to remove moisture
4. Recharge system with refrigerant

The key step in the process is evacuating the system to remove moisture. As indicated earlier, moisture in a refrigerant system creates big problems. The system may be emptied for repair by means of a vacuum pump and a standard gauge set.

To remove moisture from the system, however, the same equipment is not adequate. The vacuum pump used for normal purposes will take far too long to do the job of removing moisture. A larger pump is needed. The standard gauge set, meanwhile, measures in inches of mercury, whereas the evacuation level required calls for measurement in terms of microns. The criterion value is 450 microns. One inch of mercury equates to 25,400 microns. Coordination with the maintenance superintendent remedied this problem. Each evacuation station was equipped with a heavier pump and a gauge set capable of measuring in microns. The new measuring device is called a thermistor gauge set.

The next two examples of maintenance problems lead to difficulties in troubleshooting. Both were created by the designer. The first involves water circulation and associated controls.

As we said earlier, the water circulation subsystem (and associated controls) is responsible for coach heating. Here is what happens when the coach is in the heating mode (Figure 14): a thermostat in the control group

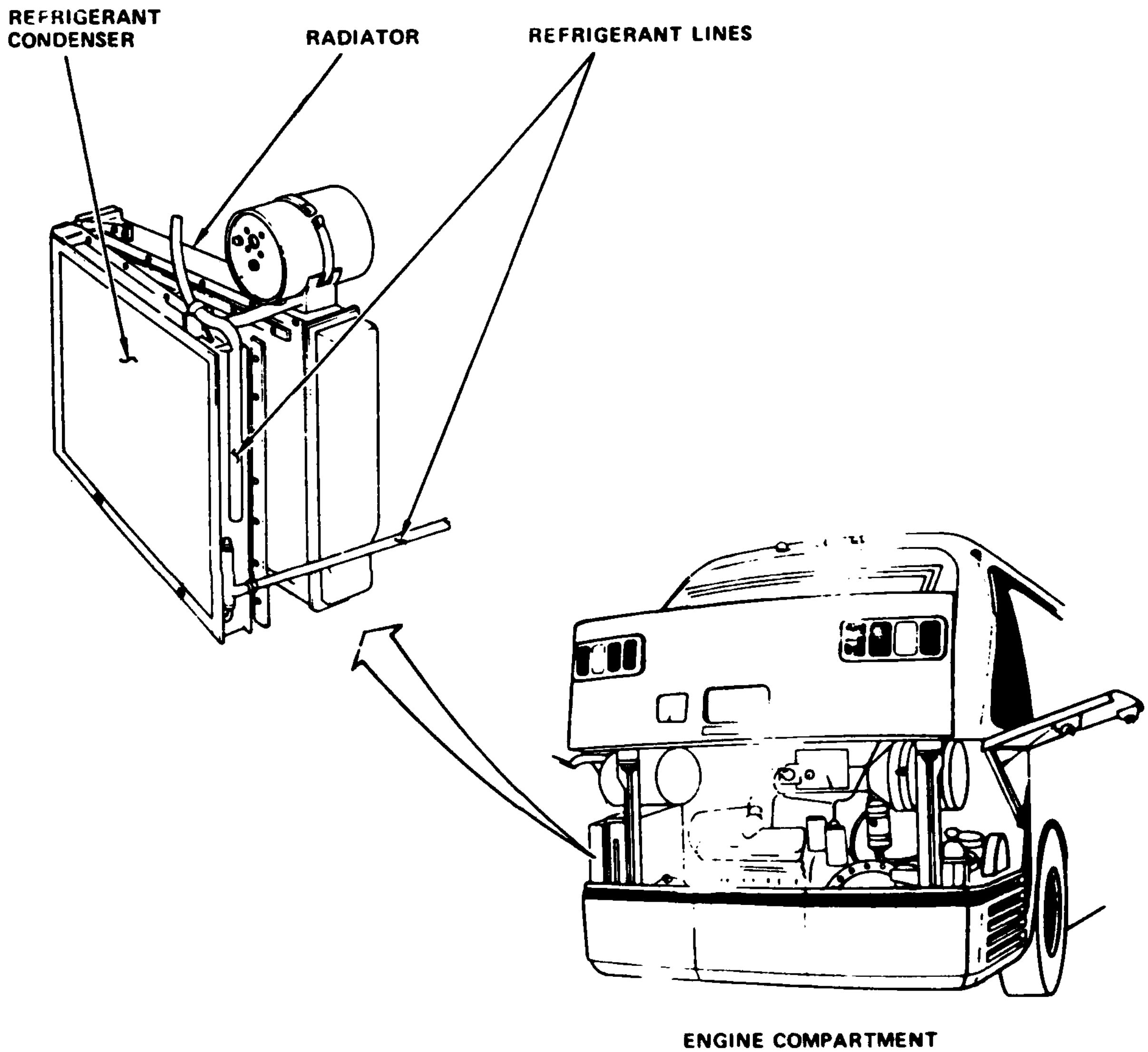


Figure 12. Improper maintenance practice.

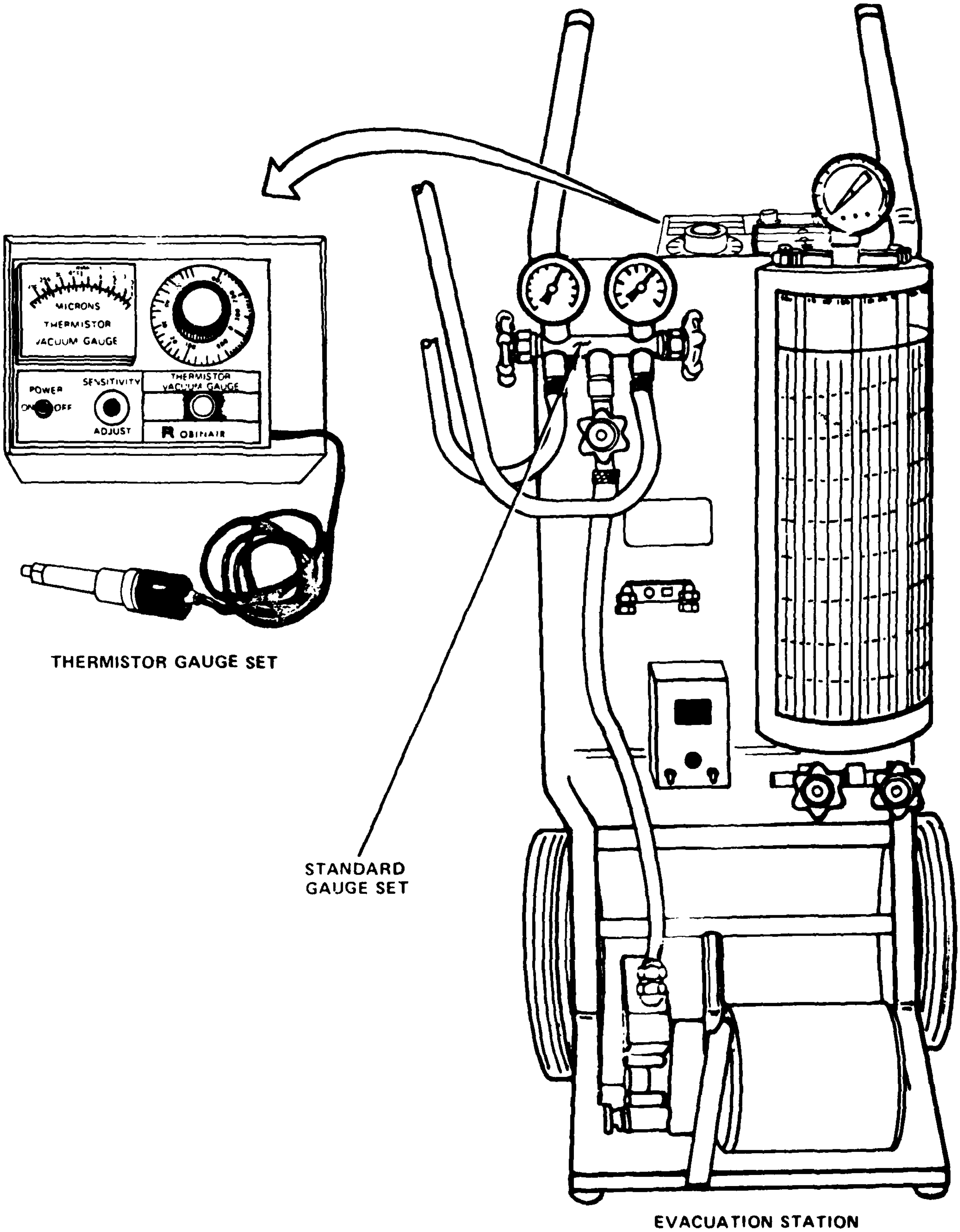


Figure 13. Improper maintenance support equipment.

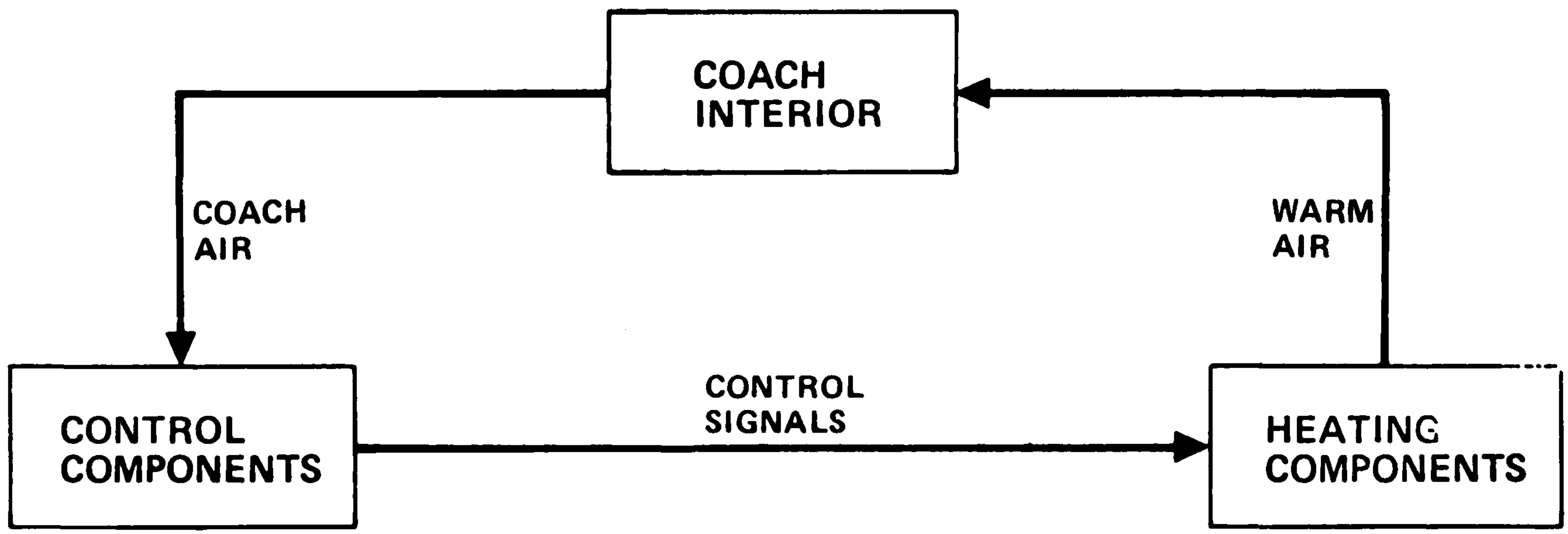


Figure 14. Coach in heating mode.

senses the temperature of the air in the coach. If the air is too cool, pneumatic control signals are sent out, activating the heating components. The key heating component is the water modulation valve which controls the flow of hot water from the engine cooling system through the heaters. If the water modulation valve and other components are working right, warm air is blown into the interior of the coach. Eventually, the temperature of the coach interior is again sensed by the thermostat and the cycle is repeated.

The process involves ten major components, plus pneumatic lines, water lines, electrical wires and connecting hardware. The problem with the existing arrangement is that, when the system fails, it is very difficult to determine which component is responsible. The design forms a closed loop unbroken by any indicators or controls. The only way to approach a malfunction is to test each item individually.

Project analysts responded to the problem by constructing a special test fixture (Figure 15). The fixture contains two controls, a pressure gauge, a hose, and connector hardware. The connector hardware allows the fixture to be installed in the existing pneumatic control line (Figure 16) running into the water modulation valve. Along with this fixture is a thermometer, placed inside the coach. With this new setup, the troubleshooter can run a variety of tests, all from one convenient location.

Figure 17 shows how the test fixture would be represented in our original diagram. Note the control and the indicator of the fixture and the thermometer in the coach. Consider now, two quick examples of the types of tests possible.

In the first example, the troubleshooter can use the start signal to the heating components. By checking the temperature of the air flow at the outlets in the coach, he can quickly determine whether or not the heating components are working. If they <u>are</u>, then the trouble must reside in the control components.

The second example applies if the heating components are working. The test fixture allows the troubleshooter to vary the amount of heat delivered by the heating components. The temperature variations are picked up by the thermometer inside the coach. For each temperature valve, a corresponding pressure valve should be registered on the test fixture indicator. Different kinds of discrepancies in the temperature/pressure relationship point to different groups of components as possible causes of the malfunction. The special test fixture has become a popular piece of hardware. The maintenance superintendent has taken steps to make it available to all garages.

The second example of troubleshooting difficulty involves the blower motor control circuits. There, all components are interconnected in such a way that the failure of any one could shut down the entire group. The blower motors are, in fact, wired in series (Figure 18).

Ideas for redesign were easily generated. One in particular is shown in Figure 19. Note that it consists merely of converting the series circuit into two parallel circuits. The advantages to the troubleshooter are obvious.

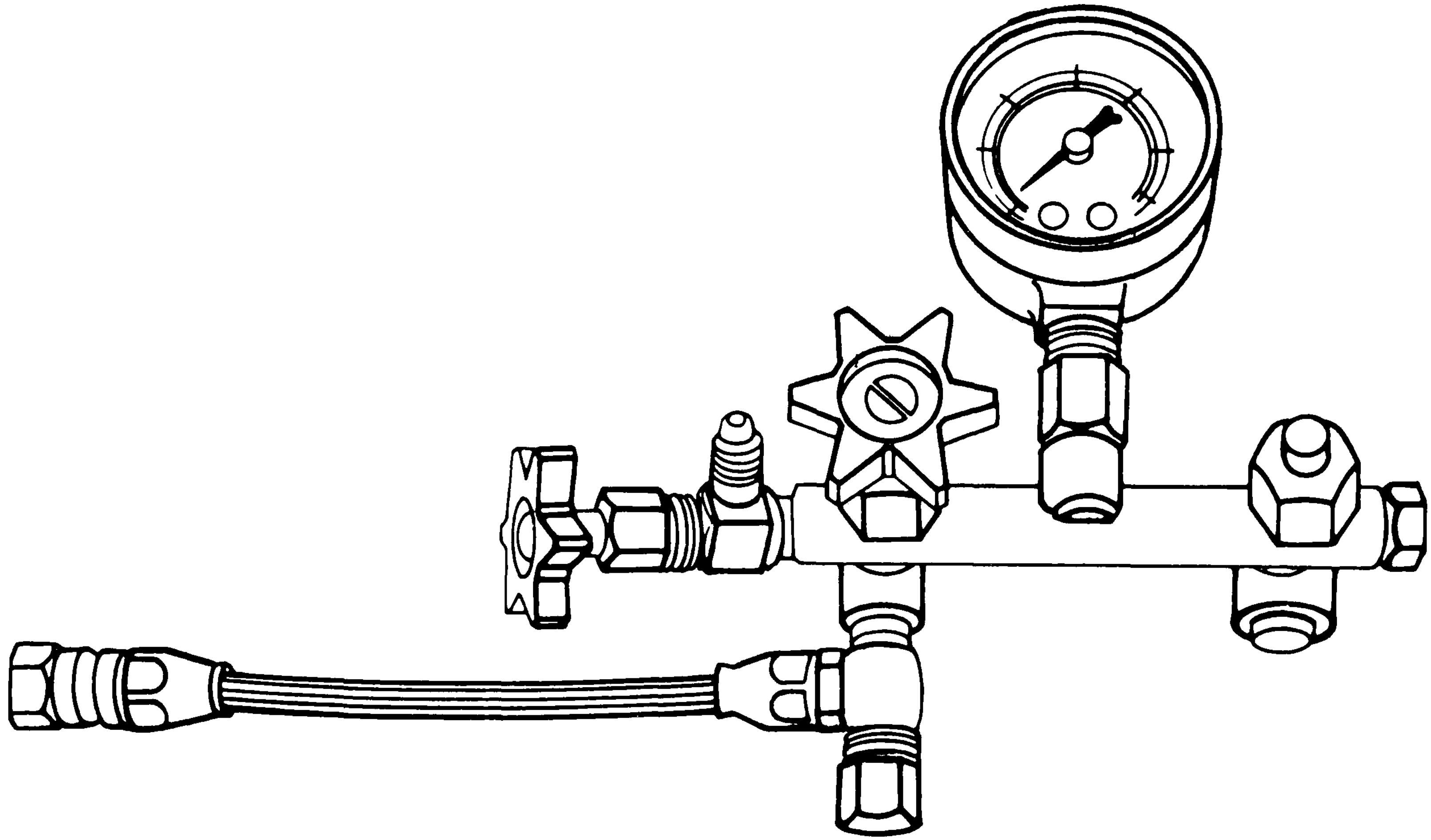


Figure 15. Special test fixture.

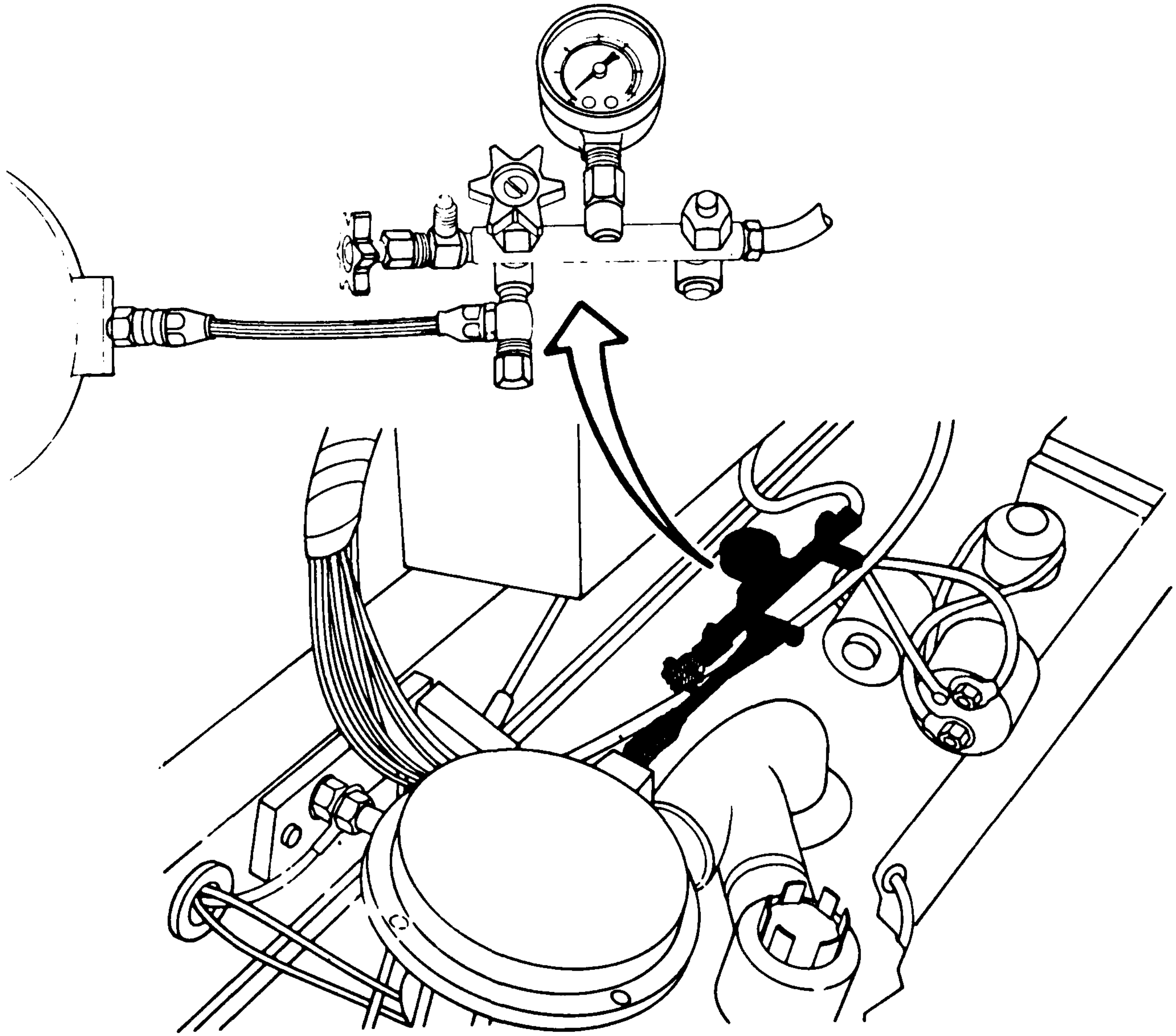


Figure 16. Heating and control checkout assembly.

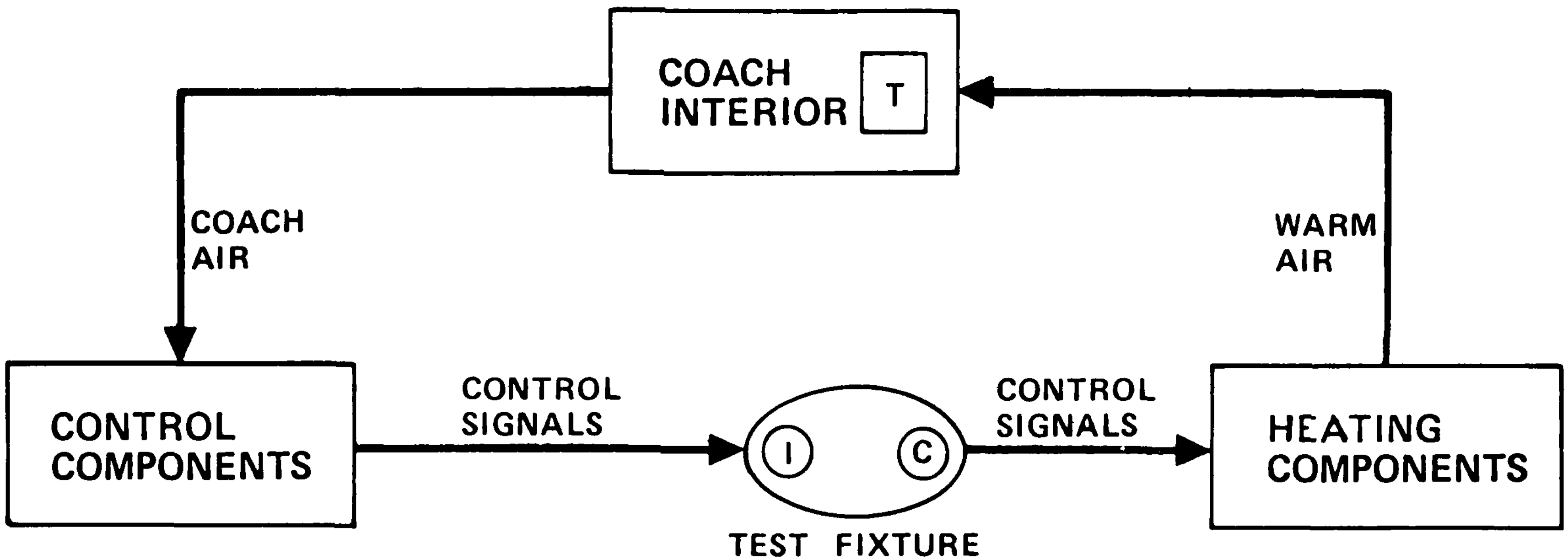


Figure 17. Coach in heating mode under test.

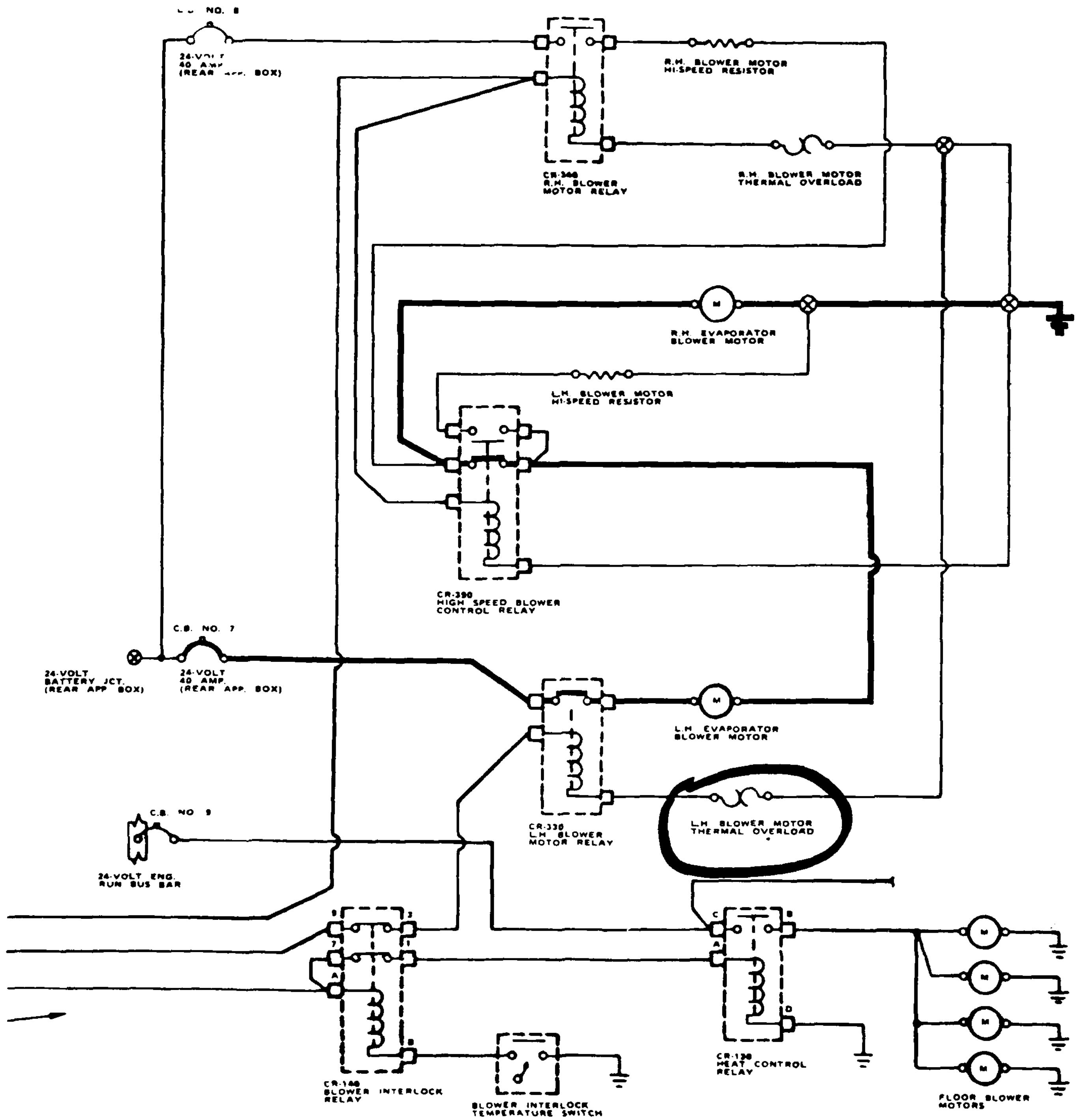


Figure 18. Blower motor control circuit (original design).

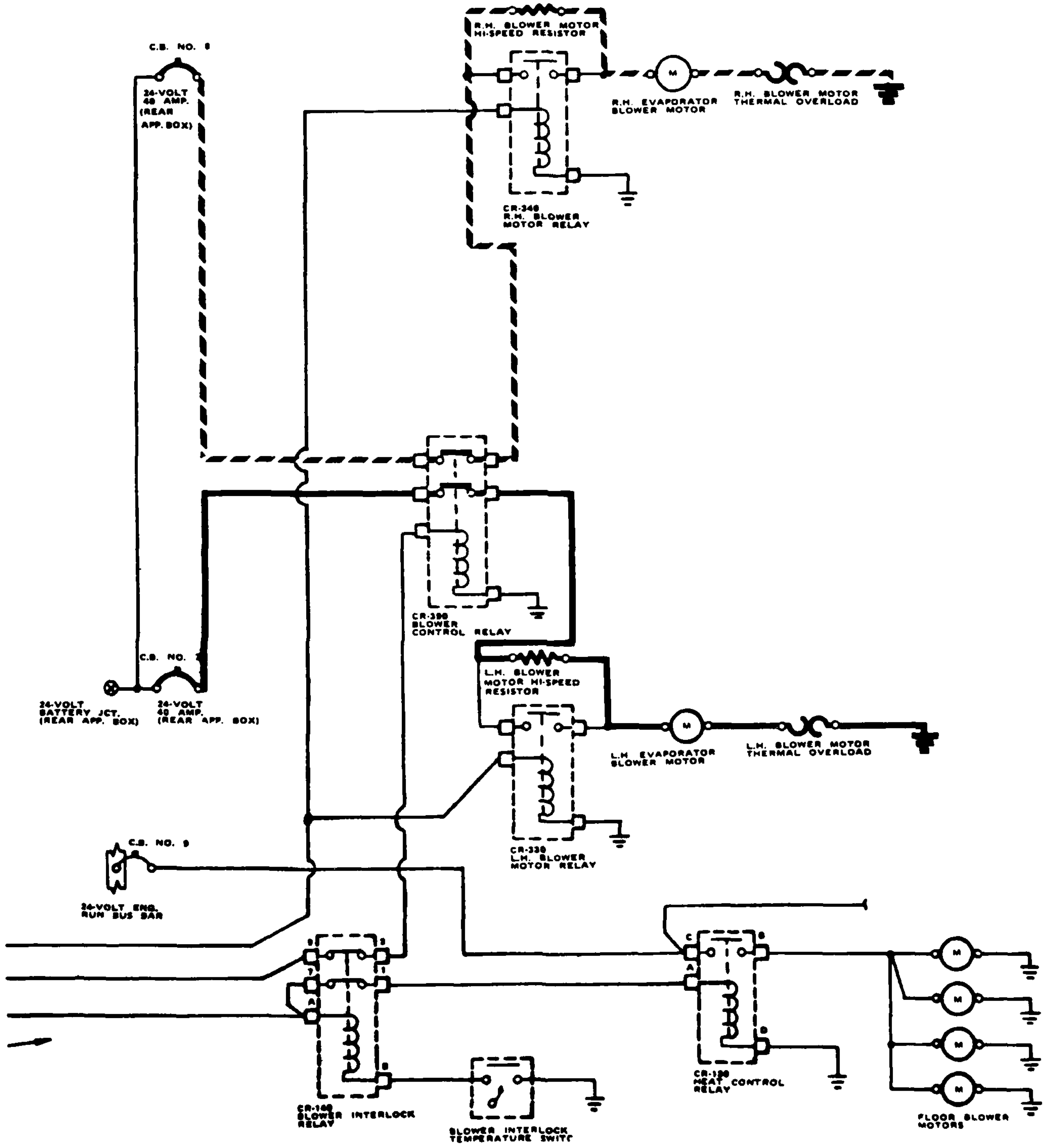


Figure 19. Blower motor control circuit (suggested revision).

Unfortunately, it was not possible to get this change authorized. The inefficient original design, thus, has had to be dealt with by careful construction of the Troubleshoot JPA.

Program Implementation

While the information products were being developed, a great deal of analysis was taking place. This analysis led to the discovery of the erroneous maintenance practices. Correction of those practices was made possible by a cooperative maintenance superintendent.

Mechanics were taken through basic training on the Heating and Air Conditioning System. Because of the power of the JPA concept, basic training was accomplished in less than 24 "hours" per class. JPAs were then placed in all the garages, at points where the mechanics could gain access to them easily.

To expand the opportunity for newly-trained mechanics to work on the system, a preventive maintenance campaign was established. It calls for direct use of key JPAs in the work. It is staffed entirely by newly-trained mechanics.

A quality control plan was adopted, calling for the work of the preventive maintenance teams to be checked for their first few experiences. A feedback loop was established whereby supervisors responsible for the preventive maintenance teams could be kept informed of their work quality. Two means were provided. One is the record generated by the quality control effort. The other is a record showing repeat jobs and the mechanics associated with them.

Program Evaluation

A special effort has been undertaken to obtain a practical evaluation of the Detroit program. This effort has involved quantitative measures applied both before and after training. One measure is based on road calls. The other is based on drive-in complaints. Both represent unscheduled maintenance actions of the type Detroit would like to avoid, whenever possible. Fortunately, the normal recordkeeping system at Detroit requires the documentation of each maintenance task action. Key data items recorded at that time are (Figure 20):

- Date of occurrence
- Coach number
- System involved
- Mechanic involved

With these elements, it is possible to construct reports that reflect performance and maintenance effectiveness. Preventive maintenance transactions are recorded separately.

Some preliminary analyses have already been made, focusing on repeat maintenance actions (Figures 21 and 22). Such repeats are taken to reflect the presence of mechanic errors. We realize, of course, that all repeats are

ROAD CALLS

CITY OF DETROIT
DEPT. OF TRANSPORTATION

SERVICE CALL REPORT

DOT 682723 CD
AUTOMOTIVE DIVISION

Call No. ______ Run No. ______

Garage ______ Date ______

Coach No. ______ Location ______ Due ______

Reported by ______ Received by ______ at ______ A.M. P.M.

Trouble reported ______

Time of arrival ______ Time reported back at garage ______

Exchange Coach No. ______

Driver sign name, number and time on this line

Mechanic's report ______

Signed

Foreman's report ______

______ Signed ______ Code # ______

All information MUST be filled in

DRIVE-IN COMPLAINTS

1807 — COACH NO
16364 — SPEEDOMETER READING
Shoe — TERMINAL
841 PM — TIME
11-22-80 — DATE

DEPARTMENT OF TRANSPORTATION

COACH CONDITION CARD

INDICATE DEFECT BY PUNCHING IN SPACES MARKED ( )

ENGINE:
( ) WON'T IDLE
( ) MISSES
( ) STALLED
( ) NOISY
( ) ACCELERATOR
( ) BROKEN FAN BELT
( ) OVERHEATS
( ) SLOW
(LEAK) RADIATOR
( ) OIL LEAK
( ) OIL PRESS LOW
(LOW) GAS
( ) BACKFIRES

BR...:
( ) SLOW
( ) GEAR
( ) (L) PULL

AIR:
NONE ( )
LOW ( )
HIGH ( )
LEAK ( )
COMP NOISY ( )

LIGHTS:
HEAD (FOCUS) (OUT) (DIM)
TAIL ( )
MARKER (R) (FR)
STOP ( )
DOOR (R) (FR)
DIRECTIONAL (R) (FR)
SIGNS (SIDE) (FR)
DOMES ( )
FARE BOX
DASH OI...

OPERATOR'S REMARKS

Defroster Putting Out "Cold Air"

OPERATOR Chester BADGE NO. 1645

MECHANIC TO LIST REPAIRS SEPARATELY

REPAIRED FRONT HEATER

29402

FRONT PORTION OF RECORD

BACK PORTION OF RECORD

Figure 20. Records identifying unscheduled maintenance.

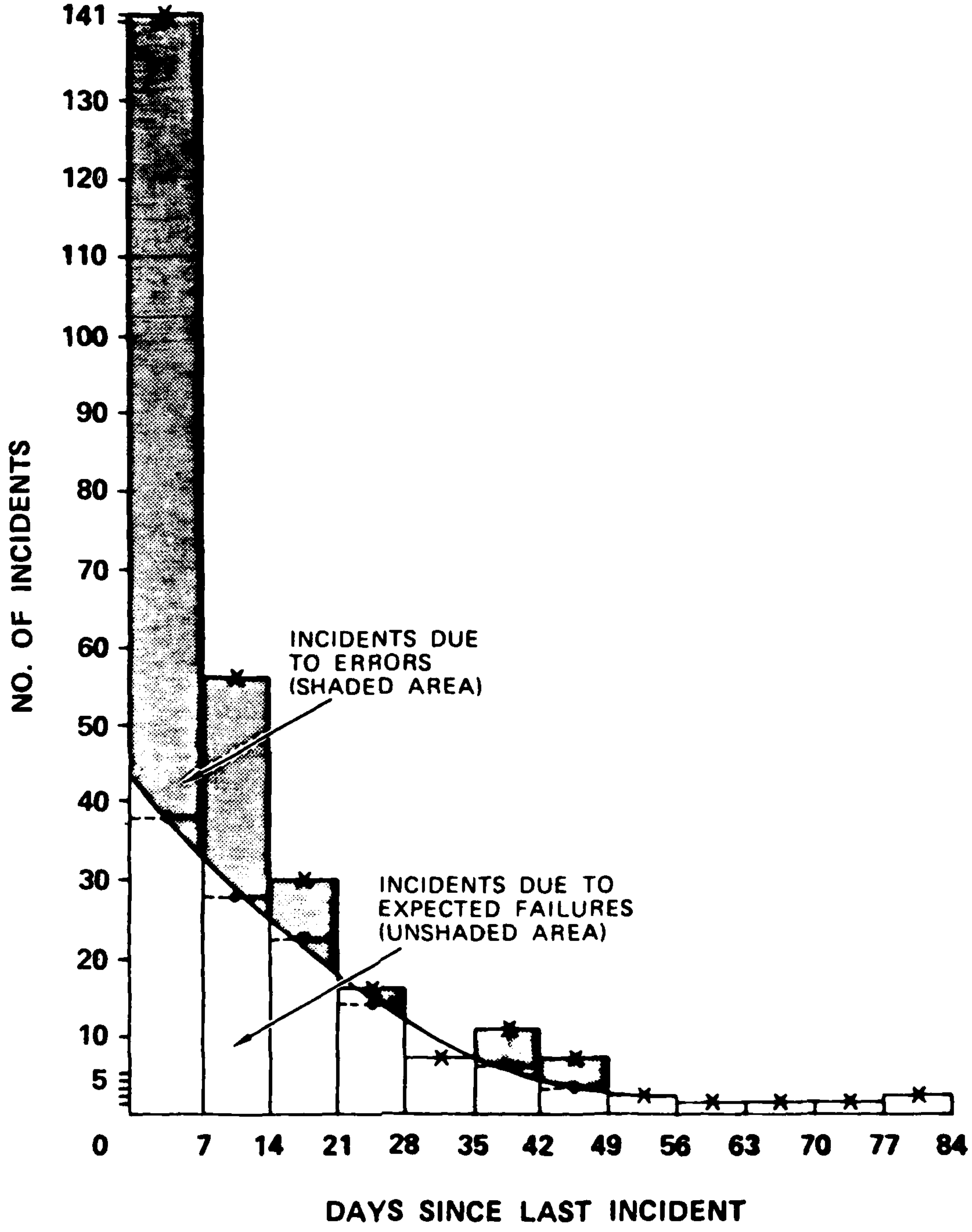


Figure 21. Repeat maintenance incidents due to error (heating and air conditioning system - summer months only).

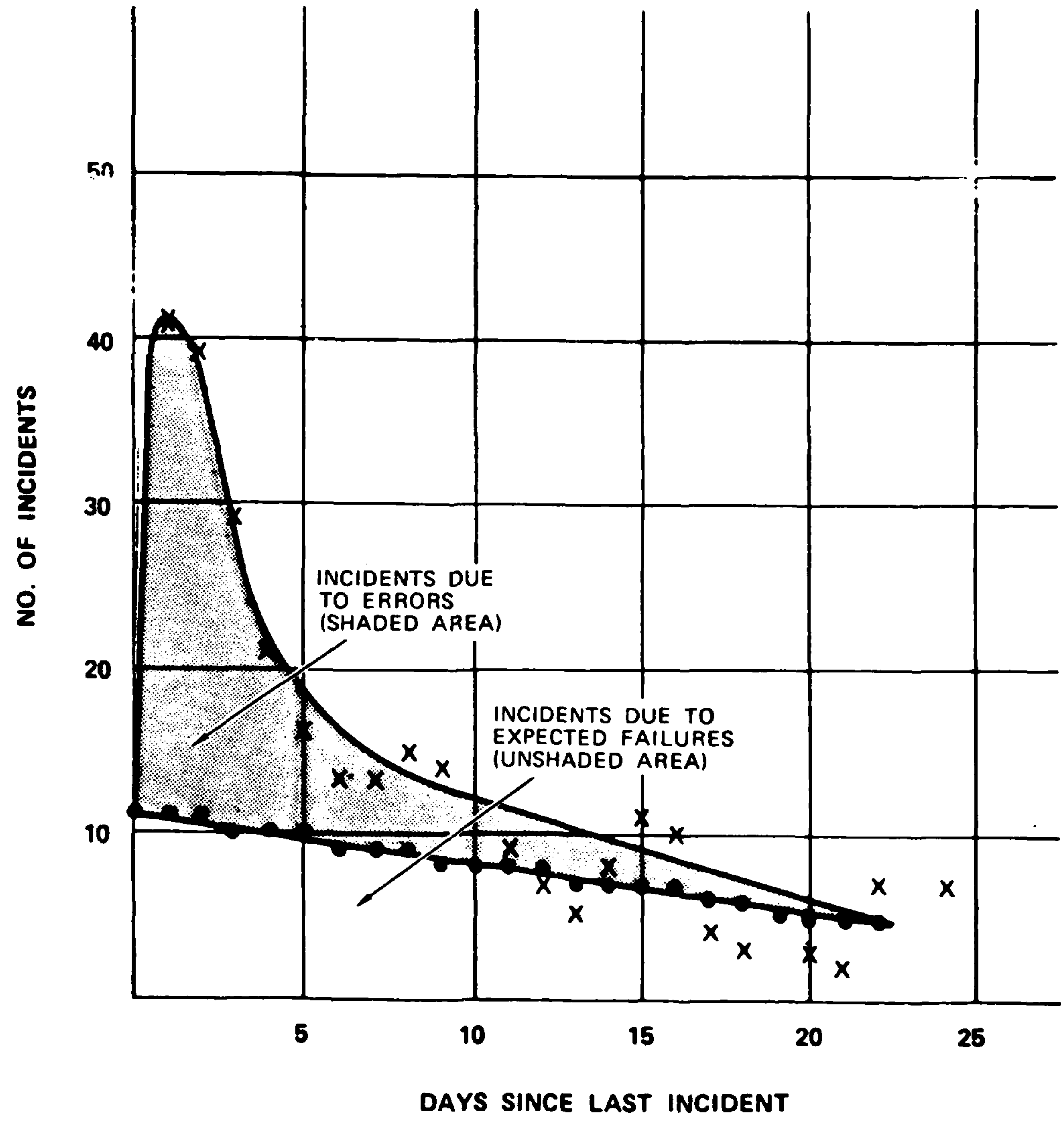


Figure 22. Repeat maintenance incidents due to error (heating and air conditioning system - summer and winter months).

Table 2

Fleet Performance Summary Drive-in Complaints

YEAR MONTH	MILES	DRIVE-IN COMPLAINTS			MILES BETWEEN COMPLAINTS			
		H&A/C	ELEC	XMSN	H&A/C	ELEC	XMSN	TOTAL
1980 SEPT	1,074,126	368	372	236	2919	2887	4551	1101
1980 OCT	905,584	196	384	196	4620	2358	4620	1167
1981 JAN	931,256	483	452	164	1928	2060	5678	847
1981 FEB	714,176	167	338	76	4277	2113	9397	1229
1981 DEC								
1982 JAN								
1983 JAN								

NO. OF RTS II COACHES: 307

Table 3

Fleet Performance Summary Road Calls

YEAR MONTH	MILES	ROAD CALLS			MILES BETWEEN CALLS			
		H&A/C	ELEC	XMSN	H&A/C	ELEC	XMSN	TOTAL
1980 SEPT	1,074,126	65	60	53	16525	17902	20267	6034
1980 OCT	905,584	37	72	50	24475	12578	18112	5695
1981 JAN	931,256	35	69	81	26607	13496	11497	5034
1981 FEB	714,176	20	39	58	35709	18312	12313	6104
1981 DEC								
1982 JAN								
1983 JAN								

NO. OF RTS II COACHES: 307

not the result of errors. Some are due to normal equipment failure. Even so, as shown here, the actual number of incidents is considerably greater than the number expected. The difference between the two represents the potential for improvement. We now believe that there are several paths to that improvement. One is better information for the mechanic. Another is better maintenance practices. Another is better equipment design, especially as it affects troubleshooting.

With specific regard to program evaluation, we are organizing fleet performance data as shown in Tables 2 and 3. That is, we are counting incidents, not repeats. And, we are referencing them against miles driven.

We have isolated the systems covered by the program. For each system, we are totaling road calls and drive-in complaints per month. This will allow us to establish a baseline record denoting performance prior to training. Data collection will be continued for a year after training. It will then be possible to compare performance in corresponding months, from one year to the next.

Conclusion

The project at Detroit has reached the point where the mechanics trained on the Heating and Air Conditioning System are about to start working in their respective garages. As indicated earlier, all known erroneous maintenance practices have been corrected and all recommended new support equipment has been obtained. A preventive maintenance campaign is scheduled to start on 15 March, 1982. Observers will be watching closely. We will know from the quantitative data to what extent we have succeeded.

The Removal of Nonfaulty Parts by Maintenance Technicians

Jesse Orlansky
Joseph String

Institute for Defense Analyses
Alexandria, Virginia

There are several reasons to be interested in how well maintenance personnel perform their job. The major one is that their performance influences the operational readiness of weapon systems in the field. Another is that knowledge about the quality of job performance is needed to evaluate the effectiveness of methods used to select and train maintenance personnel. Surprisingly, little objective data are available to document how well technicians do what they are supposed to do. Up to now, methods of selection and training have been validated almost entirely on the basis of how well maintenance technicians perform at school rather than on the job.

Measures of Job Performance

The following types of measures appear valid for describing how well maintenance personnel perform on the job:

- Number of malfunctions diagnosed correctly
- Average amount of time required to diagnose correctly various types of malfunctions
- Number of replace and/or repair actions performed per unit time
- Maintenance man-hours per operating hour
- Operational (combat) readiness of units supported by maintenance personnel
- Maintenance man-hours per maintenance requirement (action or task)
- Number of nonfaulty assemblies removed unnecessarily
- Damage to equipment during corrective maintenance
- Failure to remove faulty equipment.

This list of measures is meant to be suggestive rather than complete. If data for these measures were to be collected, they would obviously have to be based on complete records or, at least, on a representative sample of equipments, malfunctions, personnel, and working conditions.

The military services operate large maintenance management data systems that provide much detailed information on the current maintenance status of military equipment. These data systems, identified in Table 1, are discussed

elsewhere in this volume (see String and Orlansky, pp. 59). These systems were designed to provide information needed to manage maintenance and logistic services and not to relate the performance of military technicians to methods of selection and training.

There appears to be no routinely available source of data that describes the performance of maintenance personnel in any of the military services. A few special investigations (i.e., ad hoc efforts) have been reported and these provide the basis for the present paper. All of these concern only the removal of nonfaulty parts during corrective maintenance. Corrective maintenance at the organizational level is limited to "on-equipment" repair or the removal of suspect assemblies from equipment end-items. The removal of nonfaulty assemblies would appear to indicate inadequate job performance by the organizational maintenance technician. Information that nonfaulty parts have been removed arises later when intermediate level maintenance personnel cannot find a malfunction.

Data on the removal of nonfaulty parts are easy to identify and can be conveniently collected. At best, they can describe some, but obviously not all, aspects of the quality of job performance of maintenance personnel. Some qualifications on the interpretation of these data will be discussed later.

Table 1

Maintenance Management Data Systems Used by the Military Services

Service	Maintenance Management System Name	Short Title
Army	The Army Maintenance Management System	TAMMS
Navy	Naval Ships' Maintenance and Material Management System	Ships' 3-M
Navy	Naval Aviation Maintenance and Material Management System	Aviation 3-M
Air Force	Air Force Maintenance Management Systems	66-1 and 66-5

Results

A summary of seven reports on the removal of nonfaulty parts during corrective maintenance appears in Table 2. It concerns the maintenance of aircraft, armored vehicles, and the electrical components of other automotive vehicles. Some large data samples are involved, e.g., 72 F-14A aircraft over a period of one year; all maintenance actions (a total of 0.4 million actions) in the Navy on four aircraft over a period of one year; the smallest sample is for all maintenance on electrical components at an Army base for one month. The sources of the data are some of the records collected routinely by the maintenance management systems of the three Services.

Table 2

Summary of Reports on Nonfaulty Parts Removed During Corrective Maintenance

Equipment or System	Size of Sample	Period of Observation	Data Source	Corrective Maintenance Where Non-Faulty Parts Were Removed: Maintenance Echelon	Percent of Actions	Percent of Man-Hours	References
F-14A Aircraft	72 Aircraft	1 yr	3M and analyses	Organizational	4%		Gold, Kleine, Fuchs, et al., 1980, and private conversations with the authors
Armored reconnaissance and airborne assault vehicle (M 551)	Brigade	1 yr	Maintenance Request Form (DA 2407) and special form for study	Organizational	42	32%	Dressel and Shields, 1979
Aircraft: EA-6B, C-2C, SH-3H, S-3A	All Navy 1.8M man-hours 0.4M actions	1 yr	3M and interviews	Organizational Intermediate	15 16	17 9	Jewell and Webman, 1979
Electrical components: generators, regulators, alternators, distributors, starters	Fort Carson CO	1 mo		Organizational	35		Buchan and Knutson, 1977
Vehicular components				Organizational	43		Brown Board Survey, 1966
Aircraft:							
A-7D				Organizational	13[a]		Johnson and Reel, 1973
F-111A				Organizational	9[a]		
F-4D				Organizational	9[a]		
Helicopters UH-1H	82[b]	6 mo	Component removed and repair/overhaul Record (DA 2410)	Organizational	15 to 25[c]		Holbert and Newport, 1975
CH-47C	123[d]	6 mo	Component removed and repair/overhaul Record (DA 2410)	Organizational	15 to 25[c]		

a. Percent of total removals found serviceable; values estimated from a graph.
b. Number of records with failure code data; 53 other records (39 percent) had no failure code.
c. Estimated percent of transmissions found at depot to contain no defects, as reported by personnel in interviews. Due to inadequate records, study not able to compare defects reported at organizational level with those found later at depots.
d. As above; 13 other records (10 percent) had no failure code.

Nonfaulty parts were removed in 4 to 43 percent of all corrective maintenance actions in these data; the median value of 11 data sets is 15 percent. The removal of nonfaulty parts accounts for 9 to 32 percent of all maintenance man-hours (for three cases where such data were reported). According to one study, technicians fail to find a faulty part or they damage a good part in about 10 percent of all corrective maintenance actions (Gold, Kleine, Fuchs, Ravo, & Inaba, 1980).

These data suggest that inadequate performance by technicians contributes to the "not-ready" status of military equipment. Other factors would include the unavailability of spare parts, test equipment, and up-to-date technical documentation. For example, Gold et al., (1980) estimate that an average of 22 percent of the F-14A aircraft were not ready over a one-year period for reasons due to supply. According to a questionnaire, about 50 percent of 551 Army technicians believed that repetitive maintenance (same malfunction) of Army helicopters was due primarily to inadequate test equipment, trouble-shooting, and standard maintenance practices; about 20 percent gave inadequate training, tools, and maintenance manuals as a secondary cause (Holbert & Newport, 1975). These findings appear to identify a significant problem in military maintenance but do not suggest a means to its solution.

The data sample is small and may not be representative. The removal of nonfaulty parts may not always be an inappropriate action, e.g., the test equipment may not be capable of distinguishing between a faulty and nonfaulty part; if the technician is under pressure to have equipment ready for a mission, he may remove and replace a large number of assemblies without tests in order to make sure that the malfunctioning unit has been removed. Finally, the data apply to all maintenance actions within large units and not to the performance of particular individuals.

One particular value of data describing the quality of performance of maintenance personnel on jobs in operational settings would be their use in validating selection standards for recruiting and assigning personnel to career paths and for evaluating the effectiveness of various methods of training (e.g., conventional instruction compared to computer-based instruction, use of maintenance training simulators as opposed to actual equipment training). As a general matter, the effectiveness of military selection and training has been evaluated on the basis of performance of technicians at school and not on the job. The latter is the more relevant criterion.

Another possible use of these data would be to the human factors engineering of maintenance support equipment and, perhaps, of the operational equipment as well. It might be that inadequate human factors design of equipment increases the difficulty of identifying and replacing failed equipment and leads, to some extent, to the removal of nonfaulty parts.

It is conceivable that the data generated through maintenance management systems of the military services could be modified to provide information on the performance of maintenance technicians. These systems were designed primarily to manage maintenance operations and cannot be faulted for not providing information relevant to the performance, selection and training of personnel. A prototype system for providing some of this information has been

developed and is now being tested by the U.S. Army Research Institute (Katz & Drillings, 1981). Called The Army Maintenance Performance System, it records the work experience (time on each technical task in the maintenance battalion) and training (courses and qualification tests) of each maintenance technician. This record system is not meant to be part of The Army Maintenance Management System. It would be used by work supervisors and training managers; each soldier would carry his own record of experience and skill history. It does not appear that this record system would contain information about effective and ineffective performance, e.g., time to diagnose malfunctions, success and failure to diagnose malfunctions of various types.

Acknowledgement

This paper has been approved for public release, distribution unlimited.

References

Buchan, R. S., & Knutson, R. The ITDT program: The Army departs from training tradition. Defense Management Journal, January 1977, 33-37.

Dressel, J. D., & Shields, J. L. Organizational maintenance performance (Research Problem Review 79-8). Alexandria, VA: Army Research Institute for the Behavioral and Social Sciences, April 1979. (AD A076 638).

Gold, D., Kleine, B., Fuchs, F., Ravo, S., & Inaba, K. Aircraft maintenance effectiveness simulation (AMES) model: Final report (Tech. Rep. NAVTRAEQUIPCEN 77-D-0028-1). Orlando, FL: Naval Training Equipment Center, 1980.

Holbert, C., & Newport, G. Helicopter maintenance effectiveness analysis (USAAMRDL-TR-75-14). Eustis Directorate, Ft. Eustis, VA: U.S. Army Air Mobility Research and Development Laboratory, May 1975. (AD A012 225).

Jewell, E. M., & Webman, K. I. Reduction of non-defect maintenance study (Report 2-30104/9R-52146). Vought Corporation, Dallas, TX: Maintainability Engineering Group, June 1979. (AD B042 456).

Johnson, W. L., & Reel, R. E. Maintainability/reliability impact on system support costs (AFFDL-TR-73-152). Wright-Patterson AFB, OH: Air Force Flight Dynamics Laboratory, December 1973.

Katz, M. S., & Drillings, M. A direct support maintenance system. Paper presented at the First Annual Conference on Personnel and Training Factors in System Effectiveness for the National Security Industrial Association, San Diego, CA, May 1981.

Reilly, R. E. Comparative analysis of part-task trainers for U.S. Army helicopter maintenance training (PM TRADE 76-C0098-1). Naval Training Equipment Center, Orlando, FL: U.S. Army Project Manager for Training Devices, January 1977. (AD A037 359).

String, J., & Orlansky, J. Evaluating the effectiveness of maintenance training by using currently available maintenance data (IDA Paper P-1574). Alexandria, VA: Institute for Defense Analyses, August 1981.

A Survey of Methodological Issues in Maintainability Research

Shang Hwa Hsu
Charles J. Theisen, Jr.

Essex Corporation
Warminster, Pennsylvania

Maintainability, as defined quantitatively, is the probability that an equipment can be restored to operable conditions within a given period of time (Goldman & Slattery, 1977). In the past two decades maintainability has posed a serious problem for military systems. With the advent of modern technology, the complexity and the size of equipment systems has imposed severe demands on maintainers. This excessive maintenance workload has impaired operational readiness.

To overcome these maintenance burdens, a variety of efforts have been devoted toward enhancing maintainers' productivity. Researchers have been concentrating on exploring relationships between maintainability and system design parameters such as equipment design, personnel selection and training, support facilities, and the operating environment. Some human factors specialists try to apply their knowledge to design equipments that are not only minimizing maintenance errors but maximizing maintainers' capabilities, and to develop effective training methods to enhance maintainers' skill levels. Even though we recognize the importance of personnel and logistics factors, we are not dealing with these factors within the scope of the Design-for-Maintainers Program. Instead, we will concentrate on maintainability research which predicts and evaluates maintenance performance as affected by equipment design.

Maintainability research in equipment design serves three basic purposes. First, it develops methodologies for maintenance performance measurement and prediction (e.g., Shriver & Foley, Jr., 1974). Secondly, it is used to evaluate the impact of current equipment design on maintenance performance, which in turn provides diagnostic feedback to design engineers. In this light, maintainability research can serve as an evaluation tool for the development of Engineering Change Proposals (ECPs) or other weapon improvement programs. Thirdly, it is employed to determine the absolute and relative contributions of various design variables to maintenance performance, which in turn can feed into the development of a maintenance performance data base and a simulation model and provide design engineers with a basis for trade-offs

between different design features. In this vein, maintainability research acts as a ground work for the derivation of design guidelines for use in the early design phase to improve the maintainability of future equipment.

Approaches to maintainability research thus far can be classified into three categories: (1) time-synthesis methods, (2) correlational methods, and (3) experimental methods. The purpose of this survey is to describe and analyze these available approaches, and to examine the methodological issues germane to these approaches.

Current Approaches to Maintainability Research and Modeling

Quite often, maintainability requirements are expressed in terms of mean-time-to-repair (MTTR) and/or mean-down-time (MDT) because of the close relationship between these indices and system effectiveness measures such as operational availability. A number of maintainability models were developed to predict maintenance times from system and equipment design, and to provide an indication of design compliance with specified quantitative system requirements. Generally, these prediction models can be categorized into two groups: (1) time-synthesis methods, in which a "bottom-up" approach is applied. That is, it starts by defining a number of component activities in a maintenance task. The maintenance time distributions associated with these component activities are then synthesized to form the time distribution for the higher-order maintenance task. And (2) correlational methods, which predict the maintenance time of a task from scores on checklists which are designed to evaluate system design characteristics such as equipment design features, personnel requirements, and support facilities. A thorough review of these prediction models has been conducted by Rigney and Bond (1964), and Smith, Westland, and Crawford (1970). Here, only a brief description and examination of methodological issues existing in these models will be discussed.

Time-Synthesis Methods

The ARINC model, procedure I in MIL-HDBK-472, is based on the "building-block" procedure and the concept of transferability. The building-block procedure states that a maintenance task can be broken down into a number of "elemental activities," i.e., simple maintenance actions. The time distribution of each maintenance category (e.g., preparation, fault location, etc.) can be synthesized by the addition of time distributions associated with its constituent activities. These time distributions of maintenance categories, time distributions of logistics factors and administrative factors and equipment component reliability figures, in turn, synthesize into system downtime. The synthesis principle assumes that: (1) elementary activities in a maintenance category are independent of system design factors, while the frequency of occurrence of an elementary activity is affected by system design factors. The compound probability of conjunctive occurrence of several constituent activities is determined by a simple multiplication of the probabilities of occurrence of these activities. In other words, it implies that these constituent activities are discrete actions and maintainers perform these activities in some predefined sequence. The transferability principle holds that data obtained from one airborne electronic and electro-mechanical system can be generalized to those similar systems which are operated under comparable conditions. The design variables,

used as input measures in the ARINC model, are limited to the number, type, and location of components. The estimated measures is the time distribution of a total system downtime. The application of this model is only limited to the final phase of equipment development.

Another illustration of time-synthesis methods is the FEC model--procedure II in MIL-HDBK-472. Although the FEC model follows similar basic synthesis principles, there are several major differences between the FEC model and the ARINC model. One is that the estimated maintenance time here is taken as the sum of average times associated with maintenance task elements. Another difference is that the FEC model includes more design features and personnel requirements. The FEC model assumes that a maintenance task time is determined by the level at which maintenance functions are performed and diagnostic and repair methods are used to locate and correct failures of each part. The other difference is that the FEC model can also be applied to estimate preventive maintenance time.

There are several objections to time-synthesis methods. The synthesis principle does not always hold. It is only applicable to those maintenance tasks which are composed of a series of simple, discrete actions performed in a fixed sequence. In the real world, however, maintainers do not necessarily perform maintenance task components in a predefined sequence. Rather, they may perform some activities such as troubleshooting actions in real time. Furthermore, information and sensorimotor feedback resulting from a preceding activity tends to affect either the occurrence or the performance of the following activity in a way such that the organization of motor patterns of a maintenance action is changed or an alternative strategy is adopted. Secondly, it is doubtful that the data interpretations associated with these two models can be extrapolated to future systems. Although both models assume the generalizability of data obtained from one type of electronic equipment to other, similar types, the extent of data applicability depends on the dimensions (e.g., equipment functions, maintenance concepts, or system design, etc.) by which the systems are judged to be similar. Thirdly, both the FEC and ARINC models are rather insensitive to the effects of design variables on maintenance performance. One problem is that the design variables dealt with in these models are limited to just a few of the physical characteristics of a component or a complete system. In applying human-machine interface design principles, the models ignore the psychological attributes underlying various physical characteristics. In other words, the models fail to specify how these physical characteristics impose excessive stress on maintainers. For example, does the large number of replaceable components, which is dealt with in the ARINC model, specify the high degree of complexity of a maintenance task or other psychological factors? In fact, physical characteristics have a more profound effect on maintenance performance than the models assume. Unless these psychological variables which underlie physical characteristics are known, it is very difficult to predict maintenance performance from physical characteristics. A second major problem within the models is that the dependent measures estimated are contaminated criteria of maintainability. That is, a high system downtime or mean-active-maintenance time is a combined index of poor reliability as well as poor maintainability. Since poor design presumably exerts its major effect on maintenance time, these two specific time measures are not, in their present form, appropriate indicators of the effects of poor design on maintenance. Thus, the time

measures in these models do not provide designers with information concerning <u>how</u> to improve maintenance performance.

Correlational Methods

In the RCA model, procedure III in MIL-HDBK-472, it is postulated that the duration of system downtime is a function of such system design parameters as equipment configuration characteristics, support facilities, and personnel requirements. Therefore, system downtime can be estimated by inserting scores obtained from three design-related checklists into a linear regression equation. Moreover, the evaluation of these checklists is dependent upon the results of a step-by-step maintenance task analysis.

Although portions of the RCA prediction procedure can be used to evaluate the relative maintainability of alternative designs, this model does not allow design engineers to perform trade-offs between various design variables because the relative importance of all the design features in the checklist are assumed to be equal. Another problem in this model is related to the generalizability of the regression equation from one equipment to another. The same regression equation has been employed to predict maintainability of different equipment types. However, validity studies need to be performed across different types of equipment in order to assure this generalizability. The third problem concerns the subjectivity involved in checklist evaluation. The validity of checklist evaluation relies both on the availability of detailed information concerning design features, and on the knowledge of the scoring technique and engineering principles an evaluator has. Therefore, the prediction technique is doomed to fail if an appropriate maintenance analysis is not performed or training in engineering and psychometric principles is not available to an evaluator.

To remedy the foregoing weaknesses of the RCA model, a series of correlational studies were later done by Lintz and his collegues (Lintz, Loy, Brock, & Potempa, 1973; Lintz, Loy, Hopper, & Potempa, 1973; Potempa, Lintz & Luckew, 1975). One of the goals of their studies was to demonstrate that the multiple regression approach can be a viable method for serving as an objective estimation of maintenance performance from design characteristics. In order to investigate the impact of design features extensively and to establish a comprehensive data base, an inclusive list of design features was generated from a wide range of avionics equipments and 22 design variables were later selected on the basis of the ratings of their relative importance. Factor analyses and correlational analyses were conducted to evaluate the relationships between design features and maintenance time, and errors on checkout procedures of ten avionics equipments. Prediction equations were thus derived. With regard to organizational level maintenance performance, the findings showed that performance time can be predicted from a combination of design features such as the number of controls and displays, the reliability of test equipment, and the percentage of checkout to lowest line-replaceable-units (LRUs). The probability of committing a maintenance error can be predicted from another set of design features such as the accessibility of components, the percentage of plug-in-circuits, the percentage of connectors which can be incorrectly connected, the number of special conditions required for checkout, complexity of test equipment operation, and percentage of checkout to lowest LRUs.

The high correlations between design features and maintenance performance found in these studies suggest that the multiple regression approach can be a powerful method for predicting maintenance performance from an evaluation of design features. Moreover, these findings constitute a valuable source of hypotheses for further research. Investigators should be aware, however, of several weaknesses inherent in multiple regression analysis. One weakness is that a regression analysis only tells design engineers what design features affect maintenance performance. Questions as to how design features influence maintenance performance still remain unanswered. Therefore, the regression method does not lead directly to firm design specifications. The second weakness of multiple regression is that the reliability of regression weights decreases when a large sample size is not available and the number of independent variables is relatively large. Even though some attempts have been made to reduce the number of independent variables by performing a factor analysis beforehand, it is very difficult for design engineers to use those "factors," derived from the factor analysis, as guidelines in designing equipment. Another weakness of multiple regression is that it is very difficult to determine the relative contributions of various independent variables when those independent variables are intercorrelated. Unfortunately, that is the case in maintainability research. For example, one can expect a correlation between the accessibility of components and the complexity of maintenance procedures. Without knowing the relative merits of various design variables, it would be difficult to construct a model which yields data for design decisions. It has been shown that correlational methods have certain weaknesses and it will take some work to improve them before they will be ideally suited to our needs. In the meantime, one of the major emphases will be to define the design variables quantitatively in psychometric terms and in terms useful to the engineer.

Laboratory Experiments

While time-synthesis methods and correlational methods have shown some success in predicting maintainability of a design choice, these methods do not provide design engineers with information as to how to reduce maintenance workload by way of equipment design and further, what an alternative design might be. This deficiency results from a lack of knowledge of the processes or mechanisms through which design factors make an influence. Recently, investigators began to address this issue through controlled experiments in laboratory settings.

In a laboratory experiment, a maintenance task is broken down into several behavioral components and processes, i.e., psychomotor, conceptual, and perceptual. An experiment is then designed to investigate the impact of design factors on one piece of the behavioral components or processes. Quite often, the removal and installation processes are examined in a psychomotor skill domain. The troubleshooting and checkout processes are treated as cognitive processes; some times as a problem solving process, other times as a perceptual process.

Recent studies have concentrated on investigation of troubleshooting processes and the development of optimal troubleshooting strategies because troubleshooting consumes the majority of maintenance time. A family of troubleshooting strategies has been devised. The effectiveness of these strategies will be examined across different equipment designs.

The major deficiency of laboratory experiments is the generalizability of laboratory findings to the real world and the lack of their acceptance by field maintainers. As Christensen and Howard (1981) pointed out, none of the laboratory-derived troubleshooting strategies has been adopted by maintainers. One problem of laboratory experiments is that the environmental fidelity is often ignored. In a laboratory setting, environmental variables are often controlled. However, one can expect that there is an interaction, which is very important, between design variables and environmental variables. From our interviews with NAMTRADET instructors, it was found that red color-coding is ineffective for organizational level maintenance performance because red lighting is used on the hanger deck of a carrier. Another finding is that limited workspace on a carrier tends to change the maintenance task structure. If investigators ignore these interactions in the working environment, the laboratory findings may be nullified or even reversed.

The second problem with laboratory experiments is related to the measurement and definition of design variables. Rigney (1977) complained that "many of the design variables have not been suitably identified and many others have not been measured in an appropriate way" (Goldman & Slattery, 1977, pp. 254). With regard to the measurement of design variables, if the accessibility of the components is defined as the number of steps needed to reach the components, then the definition assumes that the distance between every two steps is equal, as in an equal interval scale. However, we know that this assumption may not hold true in the real world. Let us take the removal of an F-14 Sensing Element #1 as an example. In removing Sensing Element #1, the overwing fairing needs to be removed so that the sensing element can be accessed. If we define the accessibility of the sensing element as the number of steps taken in removing the overwing fairing, then we assume that the step of loosening two aft screws, and one step in removing the overwing fairing, is equal to the step of removing eight screws. These two steps, of course, cannot be regarded as equal. On the other hand, if the number of steps is measured on an ordinal scale, a two-step action is not always less than another three-step action. Another point is that some design variables may need to be defined from the viewpoint of the human-machine interface. On the issue of the complexity of design, Rouse and Rouse (1979) proposed that the definition of complexity, within the context of troubleshooting tasks, should deal with how much maintainers understand the concepts of problem and solutions strategy, as well as properties of the problem itself. They tested the validity of four measures of complexity: (1) one based on the number of components in the system, (2) one based on computational complexity, (3) one based on the number of relevant relationships, (4) one based on information theory. It was found that the last two measures are good predictors of troubleshooting performance (i.e., troubleshooting time). Therefore, they concluded that psychological perspectives should be incorporated into the definition and measurement of complexity. In this regard, a factor analysis and multidimensional scaling may be a viable method for identifying and developing design variable measures.

Furthermore, a third problem related to laboratory research is performance measures. In developing performance measures, several should be taken into account. First, performance measures employed in a laboratory experiment must be related to system criteria. At least, the relationship between maintenance performance measures used in a laboratory setting and system effectiveness

criteria should be established. Thus, the laboratory data can be transformed into the system engineering domain and accepted by engineers. Secondly, the interrelationships among performance measures should be examined. If two performance measures are independent of each other, this implies that we are dealing with two different processes rather than one. In the Potempa et al. study (1975), different sets of design features were found to be related to maintenance time, and errors, respectively. This finding may indicate that the process of producing maintenance time is different from that of maintenance errors. Therefore, one should be cautious in generalizing the data from one study to another. One way to avoid this problem is to employ a multivariate analysis in dealing with several discernible aspects of maintenance performance at the same time. In this way, maintenance performance can be investigated as a whole contruct rather than a construct torn into pieces. Finally, the measurement of maintenance performance must be developed in a way that will reflect the impact of design on maintainers' capabilities and their limitations. A task analysis may assist in the development of performance measures, especially in defining and classifying maintenance errors. The requirements and procedures of maintenance task analyses, however, need to be specified.

From the discussion of problems with laboratory experiments, some improvements need to be made in relating laboratory data to field data. The first step of this job will be to observe and analyze how maintainers perform in a field setting to aid in identifying realistic experimental variables and in developing a maintenance performance measurement scheme. Unless the important potential independent variables are suitably identified, it is not possible to investigate design effects on maintenance performance in a well-controlled laboratory setting.

Discussion and Conclusion

In the preceding discussion of current approaches to maintainability research, one can see that there is a need to develop a procedure which will enable us to identify current maintenance problems and improve maintainability of future equipment. In the identification of current maintenance problems and the derivation of solutions to these problems, a procedure is proposed. This procedure (1) includes 3-M data analysis, (2) discusses high maintenance-man-hour systems with maintenance personnel, (3) conducts a maintenance task analysis, (4) performs field observations, and (5) documents problems and develops recommendations for change. Review of 3-M data yields some indication as to which maintenance tasks should be looked at. Having determined candidate maintenance tasks, structured interviews with maintenance personnel can shed some light on the characteristics and locus of maintenance problems in a particular maintenance task and provide an important data source of design deficiencies. A maintenance task analysis further gives information concerning characteristics of basic parameters of maintenance performance and critical design variables. Moreover, field observations yield data to compare field maintenance performance with the maintenance task structure. These observations together with structured interviews, in turn, provide some insight into design rules for the particular equipment and/or component.

For the improvement of the maintainability of future equipment, design tools (i.e., design guidelines and a simulation model) which can be used in

the early design phase, need to be developed. The first step in developing these design tools will be the establishment of a maintenance performance data base. The data base will comprise two types of empirical data. One type will contain data on the extent to which critical design variables affect maintenance performance in a particular system, which in turn affect system effectiveness. The other will contain information on how a design factor interacts with other factors and how we may characterize this interactive effect so that a matrix of favorable design factors and design guidelines can then be derived. Therefore, the construction of such a data base will require a series of parametric experimentations. Before the construction of this data base, however, more precise and sensitive measurements of maintenance performance, as well as design variables, must be developed. In this vein, a task analysis can contribute greatly to the development of maintenance performance measurement. First, a task analysis can be used as a vehicle to identify specific behavioral components which should be examined. Secondly, a task analysis would shed some light on characteristics of basic parameters of maintenance performance and their relationships to system effectiveness. Therefore, it can provide a basis for relating field data to laboratory data. With respect to the measurement of design variables, psychological dimensions underlying physical characteristics should be identified. In this light, factor-analytic methods and multidimensional scaling procedures can help in determining a set of psychological factors that underlie physical layouts. In order to assure the generalizability of the data base, a functional taxonomy of maintenance tasks in various types of equipment should be examined. The functional taxonomy will document commonalities and dissimilarities in essential skills and knowledge required to maintain different equipment. This information will then enable design engineers to decide the extent to which the data may be applied to their system, viz., its generalizability.

Finally, it must be remembered that when we have developed design-for-maintainers methodologies, design engineers are likely _not_ to adopt our recommendations if information documented in the maintenance performance data base is too massive to be handled by design engineers or if the process of applying maintainability data and design principles is too complicated. Thus, we must also consider design-for-designers. We must develop ways to reduce designers' workload. That is, we need to develop a decision aid for design engineers to incorporate maintainability data and design guidelines into their design. The decision aid could be a computer "expert system" derived from artificial intelligence principles. The expert system, together with a maintenance performance simulation model, could act as an intelligent assistant, providing advice and exercising trade-offs in the design process. By interacting with the machine "expert," design engineers could achieve a design solution which would optimize both the reliability and maintainability of a weapon system.

References

Christensen, J. M., & Howard, J. M. Field experience in maintenance. In J. Rasmussen and W. B. Rouse (Eds.), Human detection and diagnosis of system failures. New York: Plenum, 1981.

Goldman, A. S., & Slattery, T. B. (Eds.), Maintainability: A major element of system effectiveness (2nd ed.). New York: Krieger, 1977.

Lintz, L. M., Loy, S. L., Brock, G. R., & Potempa, K. W. Predicting maintenance task difficulty and personnel skill requirements based on design parameters of avionics subsystems (AFHRL-TR-72-75). Wright-Patterson AFB, OH, 1973.

Lintz, L. M., Loy, S. L., Hopper, R., & Potempa, K.W. Relationships between design characteristics of avionics subsystems and training cost, training difficulty, and job performance. Catalog of selected documents in Psychology, 1973, 3, 451.

Maintainability prediction (MIL-HDBK-472). Washington, DC: Department of Defense, May 1966.

Potempa, K. W., Lintz, L. M., & Luckew, R. S. Impact of avionic design characteristics on technical training requirements and job performance. Human Factors,1975, 17, 13-24.

Rigney, J. W. Human factors in maintenance. In A. S. Goldman and T. B. Slattery (Eds.), Maintainability: A major element of system effectiveness (2nd ed.). New York: Krieger, 1977.

Rigney, J. W., & Bond, N. A. Maintainability prediction: methods, and results (Tech. Rep. 40). University of Southern California, June 1964.

Rouse, W. B., & Rouse, S. H. Measures of complexity of fault diagnosis tasks. IEEE Transactions on Systems, Man, and Cybernetics, 1979, 11, 720-727.

Shriver, E. L., & Foley, Jr., J. P. Evaluating maintenance performance: the development and tryout of criterion referenced job task performance tests for electronic maintenance (AFHRL-TR-74-75 (II), Part II). Wright-Patterson AFB, OH, September 1974

Smith, R. L., Westland, R. A., & Crawford, B. M. The status of maintainability models: A critical review. Human Factors, 1970, 12, 271-283.

Suitability of Data Provided by Maintenance Management Systems for Validating Training

Joseph String
Jesse Orlansky

Institute for Defense Analyses
Alexandria, Virginia

Purpose

This paper assesses the possibility of using data generated by the maintenance management systems to evaluate the effectiveness of alternative methods of training military maintenance personnel.

Background

Costs of training maintenance skills comprise a significant portion of the $3 billion spent each year for technical training at military schools and can be expected to increase with increases in the complexity of weapon systems. On the other hand, the potential costs of "inadequate" maintenance, in terms of increased operating costs and reduced operational capabilities, may be considerably greater than the costs of providing more extensive and more effective maintenance training.

The effectiveness of training is measured currently mainly by student achievement at school. Occasional surveys, where supervisors rate the job performance of recent trainees, can only provide subjective, rather than objective data; moreover, such surveys generally provide data only on limited rather than on systematic samples of trainees. However, the true effectiveness of training lies in the performance of personnel on the job, rather than at school, and the comparative effectiveness of different amounts and methods of training should be measured by comparing on-the-job performances of personnel trained in different ways.

Correlations between school achievement and on-the-job performance of maintenance personnel have not been established, and the development and operation of a data system for this purpose would be a costly undertaking. However, the military services currently employ extensive systems for the day-to-day management of their maintenance operations, and these systems generate extensive historical data. If these data could be used to shed light on the performance of either maintenance organizations or the individuals assigned to them, they might also provide information that would be helpful in determining the effectiveness of alternative methods of maintenance training.

Sources of Maintenance Performance Data

The military services operate five maintenance management systems; these are identified, together with their short titles, in Table 1. Taken together, these systems encompass organizational and intermediate maintenance of all military aircraft, all Army and Air Force ground equipment (including missiles), and all Navy ships and shipboard equipment (except nuclear missiles). The Air Force 66-1 and 66-5 systems employ the same reporting formats and codes; only the Tactical Air Forces use the 66-5 system while all other Air Force organizations use the 66-1 system.

We should not be surprised to find that none of these systems, at least in its present form, provides a suitable vehicle for assessing the effectiveness of training. The reasons for this conclusion lie in two different, but related, considerations. The first encompasses rather severe restrictions on the way maintenance must be documented in order to translate the data into measures of training effectiveness. The second concerns ways in which certain characteristics of current military operations, maintenance practices, and equipment may interfere with attempts to assess training effectiveness. It should be noted, however, that these systems were designed to manage maintenance operations and were not meant to be used to evaluate the effectiveness of training or other aspects of human performance.

Table 1

Maintenance Management Data Systems Used by the Military Services

Service	Maintenance Management System: Name	Short Title
Army	The Army Maintenance Management System	TAMMS
Navy	Naval Ships' Maintenance and Material Management System	Ships' 3-M
Navy	Naval Aviation Maintenance and Material Management System	Aviation 3-M
Air Force	Air Force Maintenance Management Systems	66-1 and 66-5

Characteristics of Data Needed to Assess Training

The effectiveness of alternative methods of training maintenance personnel can be evaluated by comparing how well personnel trained two different ways maintain the same types of equipment in the field. However, we have to be reasonably sure that the personnel in both groups were actually performing the same types of maintenance on the same equipments. Verifying that these conditions are met places a series of constraints on the data developed through the management system, as follows:

- The data must measure the outcome of maintenance operations in terms that provide a criterion of maintenance personnel performance.

- The data must provide unambiguous (i.e., coded) answers to four questions regarding each maintenance operation:

  -- What equipment was maintained?
  -- Why was maintenance required (i.e., the nature of the equipment malfunction)?
  -- What was done to it (i.e., the nature of maintenance performed)?
  -- Who performed the maintenance?

- The data must separately document small-scale discrete and well-defined maintenance tasks (i.e., tasks that are comparable whenever they are performed on the same subsystem or assembly or black box installed on the same model of equipment end-item, such as, remove, adjust) rather than completed maintenance that results in equipment being returned to operational status.

- The data must identify the equipment maintained at a sufficiently low level (e.g., subsystem or assembly) so that it can be associated with a single skill area related to a specific training program.

- The data must encompass a sufficiently wide set of maintenance tasks to provide a representative sample of the on-the-job skill requirements of a particular skill area.

- The data must identify individuals (or organizations) performing maintenance in a way that will allow the association of particular skill areas on the job with specific training programs.

There are four characteristics of military equipment, maintenance organizations, and maintenance practices that, where they occur, are impediments to assessing the effectiveness of training by using on-the-job performance data, as follows:

- Maintenance tasks may be performed by a group (or team) of personnel rather than only by individuals (i.e., team maintenance).

- Maintenance tasks associated with one skill area may be performed by personnel trained in a different skill area (i.e., cross-skill maintenance).

- Maintenance organizations may not be organized internally into skill-related Work Centers.

- Not all military end-items or their installed subsystems are built to standard configurations.

These features are intractable constraints on assessing the effectiveness of training from on-the-job performance data.

However, maintenance reporting systems might be designed (or current systems modified) to identify where (i.e., on which maintenance tasks) specific activities occur. Then, maintenance activity not associated with

these constraints might shed light on training effectiveness. A summary of the characteristics of the data provided by the maintenance management systems, with regard to the issues discussed above, appears in Table 2.

Assessment of Maintenance Management Systems

Table 3 denotes, for each maintenance management system, the extent to which current documentation provides data suitable for assessing the effectiveness of training or where structural inconsistencies in the data may prevent such assessments. It was developed through study of the documentation provided for these systems supplemented by discussions with knowledgeable service personnel. Note that a notation in the upper part of the table shows an impediment to assessing training effectiveness, while a notation in the lower part signifies data that permit (or support) assessments. For both sets of characteristics, the notations in the table give the maintenance systems (and the documentation they generate) the benefit of the doubt regarding their capabilities for assessing training effectiveness. That is, where uncertainties remained, it was assumed that the requisite conditions for assessing training effectiveness were met.

TAMMS

TAMMS appears to provide no capability for assessing the effectiveness of training. The Army practices both team and cross-skill maintenance in peacetime because Army units will operate in that fashion under combat conditions. A major portion of Army maintenance units are not structured further into Work Centers (WC) so that there is no way to identify the skill areas of personnel performing maintenance. In addition, the maintenance reporting format has no provision for noting where team maintenance occurs.

Ships' 3-M

The Ship's 3-M system appears to provide no capability for assessing maintenance performance (and, hence, training effectiveness) for reasons that encompass both the nonstandard nature of shipboard equipment and the data reported. Except in the area of electronics and ordnance, shipboard systems are not standardized, and ships are not outfitted to standard configurations. Even if the configuration problem was not present, the data reported through the Ships' 3-M system appear inconsistent with assessing training effectiveness of three counts. First, maintenance reporting is notably incomplete and cannot be assumed to provide representative samples of the ranges of skills for which personnel are trained. Second, data are reported only for complete maintenance actions (as opposed to individual maintenance tasks). Finally, the English descriptions and code systems used to document maintenance are inadequate to identify comparable maintenance actions.

Aviation 3-M, 66-1, and 66-5

Even though the Air Force systems (66-1 and 66-5) employ the same data-reporting forms, they display quite different potentials for assessing the effectiveness of training. The 66-5 system, that is employed only in conjunction with the Production Oriented Maintenance Organization (POMO) concept, appears to provide no potential for this assessment. Under the POMO

Table 2

Characteristics of Data Created by Maintenance Management Systems

Characteristics of Data	Maintenance Management System			
	TAMMS (Army)	Ships' 3-M (Navy)	Aviation 3-M (Navy)	66-1/66-5 (Air Force)
Applicable equipment	All equipment	All ships	All aircraft[a]	All equipment[b]
Extent of maintenance activity documentation	Total	Selected Types of Maintenance	Total	Total
Central reporting of recorded data	None	Total	Total	Total
Level of documentation	Maintenance Task	Maintenance Action[c]	Maintenance Task	Maintenance Task
Data describes (or answers)				
What equipment, at: Major system level	-	C	-	-
Subsystem or component level	C	-	C	C
Why maintenance was required	C	E	C	C
What was done to it	C	E	C	C
Who did it: Individual	-	-	E[d]	-
Work center (or skill-related shop)	-	C[e]	C	C
Maintenance organization (or more than one work center)	C		-	-

Note: C = Coded; E = English

[a]Includes aircraft, air-launched missiles, support equipment, training equipment.

[b]Includes aircraft; ground and air-launched missiles; precision measuring and other support equipment; training equipment; ground communications, electronics, and meteorological equipment.

[c]Group of maintenance tasks.

[d]Individuals performing maintenance are identified by name only in initial hardcopy forms that are retained by local units for a limited time.

[e]All work centers involved in a maintenance action are identified in one record.

Table 3

Assessment of Maintenance Management Systems

	Maintenance Management System			
	TAMMS (Army)	Ships 3-M (Navy)	Aviation 3-M (Navy)	66-1/66-5 (USAF)
Structural inconsistencies present				
Team Maintenance	X	X	X	X
Cross-skill Maintenance	X			X
Maintenance Organizations Not Structured According to Skill-Area (i.e. WCs)	X		a	a
Non-standardized Equipment		X		
Data requirements satisfied				
Quantifies a Criterion of Performance	X	X	X	X
Coded Descriptions of Maintenance Performed				
• What Equipment was Maintained?	X	X	X	X
• What was wrong with it?	X		X	X
• What was done to it?	X		X	X
• Who Performed the Maintenance?	X	X	X	X
Maintenance "Task" Documentation	X		X	X
Equipment can be Identified with Skill Area	X	X	X	X
Recorded Maintenance Representative of Job Requirements[b]	X		X	X
Who Performed Maintenance can be Identified with Skill-Area		X[c]	X[d]	X[d]

Note: WC = Work Center Code

[a]Some WCs are manned by personnel with training in several skill areas.

[b]Recording refers only to initial documentation of maintenance performed. A comprehensive capability for assessing training effectiveness would require that these data be reported to higher echelons.

[c]More than one WC, in the same skill area, may be involved in and identified with the documentation of one maintenance action.

[d]Except for WCs manned by personnel with training in different skill areas.

structure, followed by the Tactical Air Forces, the large majority of maintenance personnel are assigned to the organizational echelon where the development of cross-skill capabilities is a primary POMO policy. This policy might be implemented in several ways (e.g., by forming inter-skill maintenance teams, by assigning personnel to Work Centers other than those for which they have been trained). Maintenance data reporting in the 66-5 system appears to provide no way to identify cross-skill work that is promoted by these means. In addition, it is possible that cross-skill maintenance might be prevalent to the point where a satisfactory sample of primary-skill maintenance could not be obtained.

The 66-1 and Aviation 3-M systems may provide a restricted capability for assessing training effectiveness _if_ occurrences of team and cross-skill maintenance could be identified unambiguously and thus eliminated from analyses. This might be possible by making some seemingly modest changes to the data reported and by supplementing these data with information that is normally available in unit roster and personnel record systems. Whether the reporting system changes and supplementary data suggested here will, in fact, provide this identification requires inquiry into maintenance operations to a depth not accomplished in this study.

Team maintenance. The 66-1 system currently documents maintenance "crew size" and "start/stop" times and notes all crew changes and work interruptions that occur during the course of a maintenance task. These data appear to provide a satisfactory separation of team from individually performed tasks. However, it is not clear whether the separation provided by these data (along with other data contained in maintenance records) is reliable for all possible types of maintenance and the various conditions under which they may be performed (e.g., shift changes, interruptions for lack of parts, changes in malfunction diagnosis). Aviation 3-M currently provides no permanently retained information regarding the number of individuals contributing to a maintenance task. However, the similarities in equipments, their maintenance requirements, and maintenance organization between USAF and Naval aircraft appear sufficient to suggest that whatever data and formats would identify team maintenance in the 66-1 system would serve the same purpose in the Aviation 3-M system.

Cross-skill maintenance. Both equipments and Work Centers (WC) appear relatable to skill areas in the Aviation 3-M and 66-1 systems so that occurrences of cross-skill work should be identifiable. However, a number of exceptions were noted in examples contained in the Aviation 3-M user manuals that cast doubt on the validity of this conclusion. The extent to which WCs, in fact, specialize in one skill area: (1) may vary among maintenance or organizations as functions of size, equipment maintained, and command decision, (2) will vary among the different WCs within maintenance organizations, and (3) may vary over time within the same WC as a function of service-wide personnel availabilities. Further, as a result of workload variations, personnel may be transferred temporarily between WCs that are associated with quite different skill areas. Similarly, the extent to which skill areas can be associated with WCs also varies. All such variations, whether thay constitute normal practices or exceptions, weaken the case for identifying cross-skill maintenance, especially where the variations are systematic.

Reporting system changes. The uncertain identification of both team and cross-skill maintenance actions could be reduced if data records were to identify specifically all personnel who performed in a maintenance task. While identifying personnel in the central maintenance data files conflicts with provisions of the Privacy Act, it should be possible to name individuals in local unit records and then to process these records in ways that would provide suitable identification for analyses of training effectiveness while being consistent with the Act. For example, individuals could be preselected for analysis of performance on the basis of training and experience information in personnel records. Look-up tables could be established or special notations (flags) could be attached to their names or identification numbers as a device for identifying the maintenance tasks they subsequently perform. Where maintenance documentation identified these individuals and where neither team nor cross-skill maintenance was indicated, the records would be duplicated for analysis of performance, and the identification of individuals could then be deleted from the maintenance records submitted to central files.

Analyses of training effectiveness could then be performed without interfering with either the current maintenance management systems or the organization of maintenance. Automatic data processing of the Aviation 3-M system is currently being modified to accomplish on-line record entry and updating (instead of hardcopy and punched card) as part of the Navy Air Logistics Command Management Information System (NALCOMIS) program. As presently designed, local unit on-line records will identify personnel by name, and this information will be dropped when the local records are committed to the Aviation 3-M central tape files. It appears to be a feasible further step to provide identification of personnel in a way that would allow selection of the on-line records for analyses of their performance.

Even with these changes, a question would remain as to whether the resulting samples of maintenance performance would be representative of the job requirements of skill areas. The prospects are not promising, especially at the organizational echelon. An analysis that concentrated on recently trained personnel would be limited essentially to personnel who are not yet qualified for independent work on aircraft equipment. The Air Force has a service-wide procedure for job qualification that consists of structured OJT and performance examinations, and personnel are not permitted to perform independent work until specifically qualified. The Navy also has defined qualifications standards and OJT programs, although the Navy program is less restrictive regarding the work which can be accomplished by new personnel. It could well be that by the time an individual meets the qualification standards for independent work the impact of different formal training programs would be diluted to the point where initial differences in performance that were due to the training would be washed out.

Acknowledgement

This paper has been approved for public release, distribution unlimited.

Diagnostic Psychological Issues and
Maintenance Design Features

Douglas M. Towne

Behavioral Technology Laboratories
University of Southern California

Maintenance activity is a function of three primary factors: the human performer, the environment in which the activity is performed, and the system being restored or adjusted.

The maintainer's capabilities are determined by many factors including (1) his innate abilities, (2) his training, (3) the type, recency, and amount of experience, and (4) his motivation. The ease of performing the task can be greatly affected by the environment in which it is attempted. These factors include (1) time constraints, (2) availability and quality of test equipment, and (3) ambient conditions, such as space, temperature, stability and visibility.

The characteristics of the system itself, however, dictate the inherent difficulty of the maintenance task. The design of the man-machine interface, which may include switches, dials, controls, and test points, partially determines the ease with which information about the system can be obtained. The physical packaging affects the ease of accessing internal elements for diagnostic, repair, and replacement purposes.

The ultimate design tool would constructively guide the designer as decisions and trade-offs are considered. Unfortunately, the relationships between maintainability and system design are not yet well defined and quantified. Consequently, even automated techniques cannot currently take on creative design functions with maintainability as the design criterion. An achievable alternative, however, would be a sensitive assessment process which can evaluate a design specification in terms of its projected maintainability in some defined environment. Such a process could be used by the designer to determine the impact of alternatives under consideration, and it could be used to compare competing specifications for complex systems. Continued use of such an assessment technique could ultimately yield design principles and relationships to form the foundation of a constructive design aid.

This paper will first summarize existing approaches to maintainability assessment, and will then describe an analytical approach currently under development by this laboratory (Towne, Fehling, & Bond, 1981).

Techniques for Analyzing Maintenance Workload

The techniques which have emerged to date are only moderately successful in producing repair time estimates which correlate with actual repair time data. Unfortunately, the existing techniques tend to be specific to particular technologies or maintenance settings, they tend to offer little insight to the designer, and most tell nothing about the performance required of the maintainer. These maintainability prediction methods can be classified into the following six categories.

Empirical Extrapolation

For a new radar system, one might predict that maintainability requirements will be about like they were on an old radar system that is similar to the new one. Of course, it may be hard to say just how similar the new item is to the previous model, but a rough similarity rule may still be practically useful. At least the real-experience data should introduce some realism into expectations for the new system.

One possible empirical generalization is that variance in repair times among military equipments is largely due to the maintenance concept employed. Airborne radars and radios are serviced via module replacement policy, whereas ship and ground-based items may require troubleshooting and repair down to the piece-part level. Hence, standard deviations for airborne equipment are on the order of half an hour, as compared to about one and a half hours for large ground and ship systems.

Checklist Methods

Many factors are known to facilitate preventive and corrective maintenance tasks. Clearly, if some key test points are inaccessible, unlabeled, or otherwise difficult to use, then the equipment will be harder to service. Lists of good design and support features have been assembled, with the idea of scoring a system on the various criteria. The famous Munger-Willis list gave 241 design features which had potential significance for maintainability (Munger & Willis, 1959). A more manageable scheme derives from MIL-HDBK-472 (U.S. Department of Defense, 1966). There are three design checklists in the document concerned with: (1) physical features such as access to and display of information, the types of fault indicators, safety considerations, and so forth, (2) the need for external facilities (special equipment, etc.), and (3) the personnel requirements for successful maintenance. According to some trials at RCA-Camden, reasonable, slightly optimistic, predictions do emerge from the analysis.

The checklist procedure certainly has one thing to recommend it: the process of scoring the design and support features may bring out serious faults.

Three objectives to checklist predictions, however, are (1) the weights, though statistically derived and "objective" for the system originally studied, are seldom cross-validated on other equipments, (2) the design features scored tend to be observable and primarily independent--complicated internal features and interactions tend to be ignored, and (3) the reliability of the predictions made, and of the predictors themselves, is seldom known. For such reasons, it may be well to regard checklist reviews as useful for the

internal design staff, rather than as satisfactory quantitative prediction schemes.

Counting Methods

At the extremes, sheer numbers can seem to dominate a maintenance situation. An equipment that has 50,000 parts should be a difficult thing to service. So one indicator of fault-locating difficulty could be the number of hardware elements that the technician has to consider.

Of course, much depends on the way that the parts are arranged, and on the possibilities for block elimination of whole segments of the equipment. Several projects have tried to combine some notion of the richness of test indications with a parts count. Leuba (1962), for instance, proposed a measure in which maintainability varied directly with the number of elements in the system, and the number of symptoms which can be caused by several different elements.

Sophisticated counting techniques may yield quantitative relationships between repair time and the counted elements which are useful in projecting the likely maintenance load imposed by a system. It must be realized, however, that pure counting measures which prove to be correlated with repair time may, in fact, only be indirect indications of system size, scope, and complexity. We might equally expect measures such as system weight or system volume to also provide significant correlations. Thus, most attempts to derive a counting measure incorporate features of system structure beyond sheer number.

Cognitive Methods

A cognitive approach to projecting maintenance workload postulates specific mental processes involved in troubleshooting and seeks to identify aspects of design which bear on those processes. Such processes might include perceptual or pattern recognition systems, a memory component, as well as processes for inference. Additionally, one may characterize various strategies for troubleshooting in terms of these component cognitive skills, how they are interrelated, and when they are used. Thus, aspects of equipment design may be sought which impact these cognitive strategies via their effect on underlying cognitive processes.

While a model based on cognitive theory offers great promise, formulating the mental processes involved will be exceedingly difficult to develop for practical use in the foreseeable future.

Complexity Measures

It seems quite reasonable to look for some way of describing the "complexity" of a system and then demonstrating the precise relationship between system complexity and various aspects of maintenance task performance such as mean-time-to-repair (MTTR). Unfortunately, complexity is a difficult concept to define and quantify. Some researchers have taken the attitude that complexity is whatever affects maintenance time, which may be one of the few possible definitions. This definition, however, results in a circular process, again involving a search for any factors which correlate with maintenance time. As discussed above, such correlational techniques do not

provide a measurement tool which is sensitive to design alternatives.

Time-Synthesis Simulation Methods

Psychologists frequently break down whole tasks into simpler elements. These subtask elements are then separately studied and combined in various ways. If the subtask performance parameters are defined probabilistically, then appropriate distributions of overall performance values can be generated. If the global performance parameters agree well with those observed in the real case, then the model is said to be validated. The synthesis can be further validated if expected changes in real performance come from experimentally produced changes in the micro-elements.

Several projects have employed time-synthesis simulation with generally positive results (Rigney, Cremer, Towne, & Mason, 1966; Siegel & Wolf, 1969; Strieb, Glenn & Wherry, 1980).

The concept of time-synthesis simulation is a powerful one. Parameters can be varied easily, and hundreds of thousands of simulated task runs can be quickly computed, so that the (model) effects of possible change can be tried out.

There are challenging technical problems in all parts of time-synthesis simulation. Many problems are encountered in setting the right task descriptive level, in obtaining suitable data about human performance, and in managing the problems of task correlation and level shifting. Though some complex behavioral routines have a straightforward sequence of subtasks, it is often difficult to synthesize a troubleshooting sequence that resembles human performance. The technique described in this paper is a type of time-synthesis technique.

An Analytic Approach to Projecting Maintenance Workload

The major problem in developing a technique for assessing the impact of a design upon the maintainer is with projecting what particular actions are likely to be performed to isolate various faults. Subsequent analyses of these actions, to evaluate performance time or difficulty, for example, are manageable problems once the constituent actions are specified.

An ideal technique would project maintenance performance across a wide range of proficiency and environmental levels, allowing designers and planners to evaluate the sensitivity of the design to those variations. Such a technique would reflect the variations in maintenance efficiency, as well as the possibly more significant variations in error commission, error severity, and error detection.

A more attainable approach, pursued here, compares and evaluates designs based on projections of performance in a normal environment in which tests are performed correctly (but not necessarily interpreted correctly). Such a capability may provide the basis for extrapolating to more error-prone performance at a later time.

The variations of possible performance are, of course, immense. At one extreme is optimal performance; the strategy employed minimizes the time expected to find and resolve a failure. At the other extreme is a strategy in

which tests are selected at random; no consideration of efficiency is made. In between are a vast array of nonoptimal maintenance task sequences which reflect individual skills, training, and abilities. We have formulated eight generic troubleshooting strategies in this domain, which, when applied to a specific representation of a system design, generate troubleshooting action sequences. Times to perform these sequences are then computed by retrieving and accumulating predetermined, standardized motion times for the actions involved. Each performance sequence and time, therefore, reflects the total impact of the system design upon the maintainer, if he were to follow the particular strategy. Moreover, any design change which would affect the maintainer would also affect the synthesized task sequences and/or the performance times of the constituent actions.

System Representation

To represent a system design, we require (1) a characterization of the symptom information regarding the state of the system, which can be accessed by the technician, (2) reliability data, (3) data expressing the "cost" of acquiring that information, and (4) a representation of the physical structure of the system.

The first two of these can be organized as a matrix as shown in Figure 1. The columns in the body of the matrix represent replaceable units (RUs) while rows represent tests. Each cell entry, S_{ij}, expresses the consequence upon $test_i$ of a failure in RU_j. An entry of zero indicates no effect, i.e., $test_i$ is unaffected be RU_j. A nonzero entry indicates an abnormal symptom.

	REPLACEABLE UNIT					
TEST	1	2	3	4	5	6
1	S11	S12	S13	...		S16
2	S21					
3	S31					
4	.					
5	.					
6	.					
7						
8	S81					S86

R1	R2	R3	R4	R5	R6

Figure 1. Symptom-malfunction matrix with test costs and unit reliability.

The physical structure of the system will be represented as an indentured assembly specification as shown in Figure 2. All system elements appearing in

the first (leftmost) column are accessible to the maintainer; the time to remove and replace each is entered in the last column. An element appearing in the second column is accessible only by first removing the element which appears above it in the first column, and so on. Tests are included in this structural representation to indicate what disassembly must be accomplished to initiate each. The test times shown are, therefore, the inherent times which are independent of preceding work.

ASSEMBLY LEVEL				
1	2	3	4	TIME (MIN.)
MODULE 1				.45
	4 COVER SCREWS			2.12
		CKT BD A		.23
		CKT BD B		.36
			TEST 4	.36
			TEST 7	.19
MODULE 2				.38
	TEST 2			.36
	CKT BD A			.36
		Q3		12.44
		R5		9.35

Figure 2. Assembly specifications.

Fixed sequences. Some portions of maintenance procedures are well defined--calibration procedures are fully proceduralized; some fault localization procedures are prescribed often by the technical documentation or are dictated by built-in test functions; and most replacement procedures are predictable from knowledge of the system structure. While individual technicians may differ in workspace and efficiency of performing, the technical documentation and system design constrain the actions which can correctly be performed.

The time data for performing tests and assembly/disassembly actions may be based upon estimates, micromotion analysis, or a mixture of these. Estimates would be used when design specifications are not detailed, or when highly precise results are not required or justified.

Micromotion analysis is the synthesis of a defined task from small, preanalyzed motions (Karger & Bayha, 1966). While this approach yields

accurate results and detailed motion documentation, it requires considerable training and application effort. An example of a micromotion analysis of connecting a coax connector to a receptacle is shown in Figure 3. Fortunately, a wide variety of testing, assembly/disassembly, and repair operations have been analyzed and documented in task time data banks. Consequently, a time value for a task may be retrieved from such a catalog, rather than being built up from detailed motion analysis. An automated technique, similar to one now used in industry (Towne, 1968, 1980), will be developed as part of this research to further facilitate this data retrieval process.

DESCRIPTION	MOTION SYMBOL	TIME (MIN x 1000)
1. Reach to Coax Connector	R14B	8.6
2. Grasp Connector	G1A	1.2
3. Move Connector to Receptacle	M14C	10.1
4. Move Connector onto Receptacle (edge hits pin)	P2SSE	11.8
5. Turn Connector to Engage Pin in Slot	P2S3	9.7
6. Release Connector	RL1	1.2
	TOTAL:	42.6 (.0426 minutes)

Figure 3. Micromotion analysis - attach coax connector to receptacle.

Variable sequences. Performance generated by individual technicians to isolate a fault is difficult to predict. Individual differences lead to a wide variety of approaches, each involving differing amounts of cognitive and manual labor. In addition, errors are often committed. Some of these are reasoning faults which merely delay the identification of the true fault. Others lead the technician on a long and fruitless search which must ultimately be abandoned if the fault is to be found. Other errors are manual in nature, and may be insignificant, moderate, or catastrophic. The objective, therefore, is to formulate a technique for generating action sequences which are typical of some representative population of maintenance technicians. The time and difficulty of performing the representative procedures may then be determined. Ideally, this process yields not only a mean (or expected) repair time, but also provides a measure of likely variation.

We have formulated a family of eight primitive troubleshooting strategies (Figure 4) to represent the possible approaches employed by individual troubleshooters in particular situations. When applied to a representation of a system, these strategies produce fault trees whose structure and performance time cost are a direct result of the system design (as well as the underlying strategy which produced them). Moreover, the fault trees are quite sensitive to even minute design changes--removing an indicator, changing the number of screws securing a module, or adding a test point would all be examples of design actions which would impact the fault trees.

		VARIABLE CONSIDERED		
NO.	STRATEGY	TEST TIME	TEST POWER	RELIA-BILITY
1	Optimum Test Selection	YES	YES	YES
2	Element Half-Splitting, Per Unit Time (ignore element reliabilities)	YES	YES	NO
3	Briefest Productive Test Selection	YES	NO	NO
4	Half-Splitting by Reliability (ignore test time cost)	NO	YES	YES
5	Half-Splitting by Element	NO	YES	NO
6	Check Least Reliable Element, Per Unit Time (ignore test power)	YES	NO	YES
7	Check Least Reliable Element	NO	NO	YES
8	Random Test Selection	NO	NO	NO

Figure 4. Eight generic fault isolation strategies.

For each strategy, a particular rule is applied to select each test. The optimum strategy, for example, says to select the test which is likely to return the most information for the time invested in performing the test. The symptom-malfunction matrix then indicates which system failures would give a normal indication and which would cause an abnormal indication for that test. The selection rule is again applied to each resulting subset, and so on, until a complete fault tree is developed (Figure 5). The time cost of isolating each element is then computed as the sum of the times of all tests which appear in the branch terminating at the element. The measure of effectiveness

of a fault tree is expected fault isolation time, computed as:

$$E = \Sigma R_i \quad t_i$$

where E is Expected fault isolation time
R_i is the Reliability of element i
t_i is the time to isolate element i, that is, the sum of all test times in the branch terminating at element i.

Thus, in Figure 5, the expected fault isolation time is 8.6 minutes.

The three variables, considered in various combinations by the strategies, are test power (the extent to which the test is likely to separate the possible faults into subsets), test performance time, and element reliability. Strategy 1 considers all three of these, and produces a fault isolation procedure (tree) which is optimal, i.e., the expected fault isolation time is minimal.

This strategy is determined by computing, at each stage in the troubleshooting process, that test which provides the maximum information per unit time. Information is computed according to Bayes' theorem as the reduction in the total system uncertainty, i.e.:

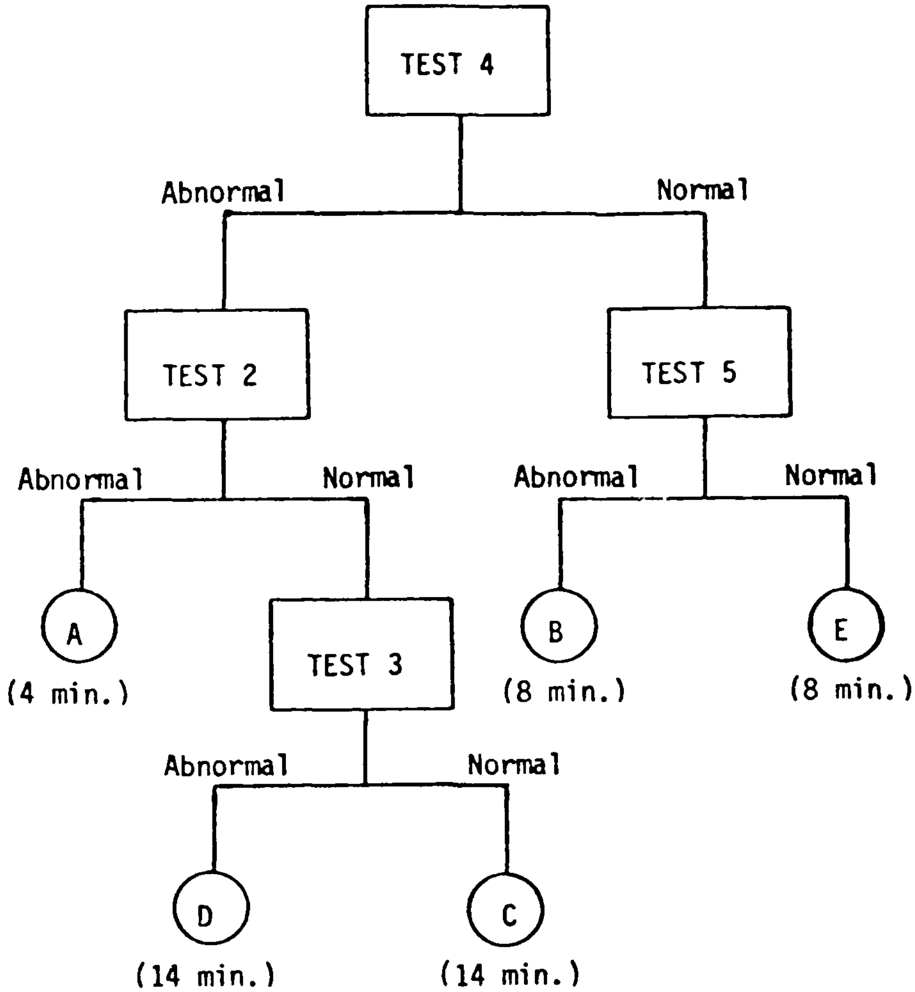
$$\Delta U = \Sigma\ p_i \ \log_2 p_i - \Sigma p_i' \ \log_2 p_i'$$

where ΔU = uncertainty reduction
p_i = probability of ith malfunction prior to test
p_i' = probability of ith malfunction after test

In general, this algorithm may not yield a true minimum, as the stepwise process does not consider the characteristics of the fault areas discriminated at each stage. A dynamic programming formulation was implemented to compute a true minimum. This process essentially "looks ahead," down each branch of the fault isolation tree, and is able to generate a slightly more efficient strategy. In one application of the Bayesian process, the expected troubleshooting time for a system was 11.702 minutes, whereas the dynamic programming process yielded 11.568 minutes. If this close correspondence between results holds up for other systems, we will employ the Bayesian processor to estimate the optimum, as it is a rapid computation compared to the heavy computation load of dynamic programming.

It must be emphasized that the compute load to generate the optimum used here was not considered by the processor itself, i.e., the definition of optimality does not embrace time invested in producing the result. Human performers, on the other hand, seem to be quite sensitive to the time costs associated with planning their performance. Field troubleshooters have at times been criticized for performing tests when more planning and analysis seemed more productive. Whether or not maintainers tend to "under-plan," it is important to distinguish between machine-computed solutions, and those developed in real time by human maintainers who forego manual performance to conduct cognitive tasks.

At the opposite extreme is a strategy in which tests are selected at random from the set of all tests which can offer any information about the



RELATIVE RELIABILITIES		TEST TIMES (MINUTES)	
A	.3	1	6.0
B	.1	2	3.0
C	.2	3	10.0
D	.1	4	1.0
E	.3	5	7.0
	1.0		

$$E = R_A T_A + R_B T_B + R_C T_C + R_D T_D + R_E T_E$$
$$= .3(4) + .1(8) + .2(14) + .1(14) + .3(8)$$
$$= 8.6 \text{ minutes, expected fault isolation time}$$

Figure 5. Simple fault isolation tree.

status of the system. The random strategy provides an upper limit on rational troubleshooting time.

Between the optimal strategy and the random strategy (on the dimension of effectiveness) lie six rational, suboptimal approaches, each of which considers one or two of the three variables used by the optimum strategy. A brief summary of all eight strategies follows.

1. Optimum test selection. Tests are selected to minimize total expected fault isolation time. This strategy considers the time costs of the tests, the power of the tests, and the relative reliabilities of the system elements.

2. Element half-splitting, per unit time. Tests are selected to best split the suspected elements into two subsets of equal size, per unit time. This is similar to strategy 1 with initial element reliabilities ignored.

3. Briefest test solution. The briefest test which can provide any information is selected at each stage. Only time cost is considered in the selection.

4. Half-splitting by reliability. Tests are selected to best split the suspected elements into two subsets of equal failure probability. This is similar to the strategy with test time cost ignored.

5. Half-splitting by element. Tests are selected to best split the suspected elements into two subsets of equal size. This is equivalent to strategy 2 with test time cost ignored.

6. Check least reliable element, per unit time. Tests are selected to monitor the greatest probability of failure per unit time. Test time cost and element reliability are considered.

7. Check least reliability element. Tests are selected to check the least reliable elements first. Only reliability is considered in the selections.

8. Random test selection. Tests are selected at random (no repeating) without regard to test time cost, test power, or reliabilities.

These eight strategies were applied to a microcomputer system consisting of mainframe, video terminal, hardcopy printer, and disk drive unit (Figure 6). The representation of the system is shown in Figure 7.

Experimentation is now underway to determine how actual troubleshooting action sequences compare to these baseline strategies. A comparison of the eight strategies, summarized in Figure 8, is interesting in its own right. The simple strategy of performing the briefest productive test (strategy 3) yielded an expected fault isolation time of 13.5 minutes, surprisingly close to the 11.7 minute optimum. Strategy 2, which uses test power and test cost, yielded 13.2 minutes expected fault isolation time, indicating that initial reliability contributed little to the solution. The classical half-splitting strategy (perform a test to split the system in two) yields 21.3 minutes, whereas half-splitting into two equally reliable subsets (strategy 4) requires less time at 16.8 minutes.

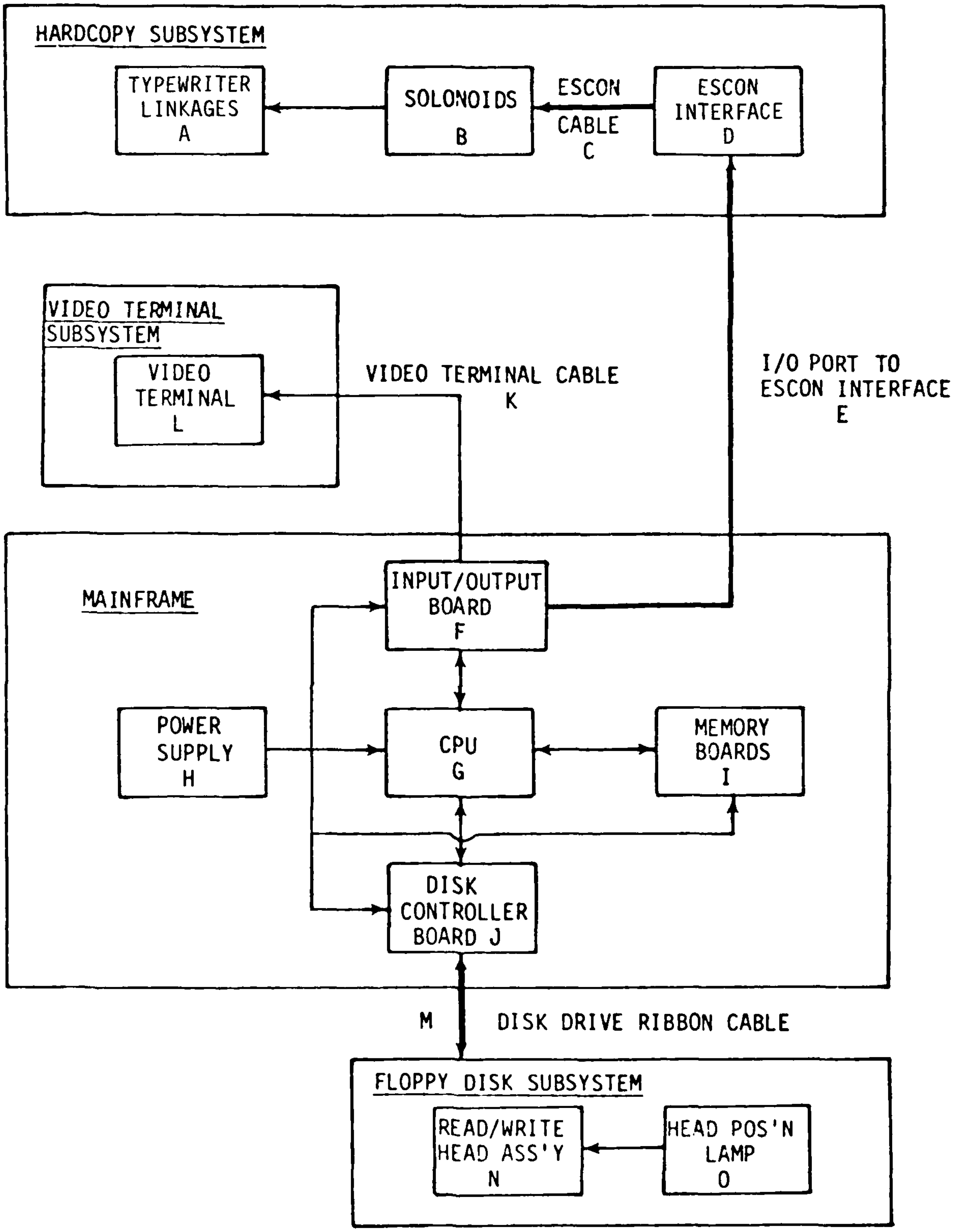


Figure 6. Microcomputer block diagram.

	REPLACEABLE UNITS															
TEST	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	TEST TIME (MIN.)
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.5
2	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	4.0
3	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	10.0
4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	12.0
5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	9.0
6	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	7.0
7	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	10.0
8	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	15.0
9	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	55.0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	13.0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5.5
12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2.0
13	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0	1.0
14	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	3.5
15	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1.0
16	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0	1.5
17	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	6.0
18	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	11.0
RELATIVE FAILURE PROBABILITIES	.219	.146	.007	.037	.007	.055	.044	.031	.073	.088	.007	.023	.007	.146	.110	

Figure 7. Representation of microcomputer system.

The two strategies which emphasize checking unreliable elements perform poorly, at over forty minutes. These results are surprisingly close to random test selection (Figure 8), which yields a mean expected repair time of 49.7 minutes (N=800).

Examination of Figure 8, reveals that the rank-order of fault isolation times for individual faults are relatively consistent across strategies. Those approaches which ignore test time cause the greatest departures from this tendency, since they may call for performing lengthy tests to check just a few unreliable elements.

STRATEGY [1]

ELEMENTS [2]	1	2	3	4	5	6	7	8
A	13.5	20.5	20.5	8.5	23.2	7.5	7.5	NOT COMPUTED
B	18.0	18.0	18.0	20.5	27.0	28.5	19.5	
C	29.5	29.5	29.5	35.5	23.2	71.5	125.5	
D	18.0	18.0	18.0	25.5	27.0	66.5	107.5	
E	20.5	13.0	13.0	42.5	19.0	78.5	116.5	
F	12.0	12.0	12.0	31.5	22.0	62.5	102.5	
G	9.0	9.0	9.0	8.0	8.0	54.0	105.0	
H	5.5	5.5	3.5	32.5	32.5	54.0	105.0	
I	2.0	2.0	2.0	32.5	32.5	114.5	92.5	
J	9.0	9.0	9.0	8.0	8.0	11.0	37.5	
K	27.0	27.0	27.0	46.5	37.0	159.5	124.0	
L	27.0	27.0	27.0	46.5	37.0	159.5	124.0	
M	29.5	29.5	29.5	42.5	19.0	89.5	125.5	
N	7.5	7.5	9.0	10.3	16.0	51.5	32.5	
O	7.5	7.5	9.0	10.3	16.0	16.5	34.5	
EXPECTED TIME	11.7	13.2	13.5	16.8	21.3	43.1	46.9	49.7

[1] See Figure 4

[2] See Figure 6

Figure 8. Element isolation times (minutes) for eight generic strategies.

The results of this one analysis certainly do not constitute a basis for generalization. Since the optimum strategy provides a true baseline of expert performance, it may prove to correlate best with observed maintenance activity, across different systems. If maintainers are generally parsimonious with time but not particularly prone to consider test power, then we may find

actual maintenance performance resembles that of strategy 3. If, instead, maintainers focus their attention on unreliable elements, then we might expect performance more like strategy 7. And, if maintainers switch among time-dominant, reliability-dominant, and test power-dominant strategies, we might expect some function of strategies 3, 5, and 7 to provide a projection of maintenance workload. For example, if there is a tendency to select quick and easy tests early in a problem, and later shift to an enumerative search process as the possible faults emerge, we may employ strategies 3 and 7 to project the performance. Experimentation is needed to determine if such shifting strategy techniques are used by maintainers, and if so, to determine when and under what conditions in a fault isolation task such shifts will occur.

The most intriguing result of this one application is that the fault isolation performances and times were relatively constant across the time-dominant strategies, and were relatively constant at a higher level across the two reliability-dominant strategies. This suggests the interesting and very tentative hypothesis that the work required to isolate a particular fault may be highly determined by the design and less sensitive to individual differences of isolation method. Further application and experimentation are needed to test these early impressions.

Acknowledgement

This work was funded jointly by the Office of Naval Research and Naval Air Development Center under Contract No. N00014-80-C-0493.

References

Karger, D. W., & Bayha, F. H. Engineered work measurement. New York: Industrial Press, 1966.

Leuba, H. R. The symptom matrix (Pub. No. 4607-1-294). Washington, D.C.: ARINC Research Corporation, 1962.

Munger, M. R., & Willis, M. P. Development of an index of electronic maintainability--A research report. Fort Monmouth, New Jersey: U.S. Army Signal Support Agency, 1959.

Rigney, J. W., Cremer, R. H., Towne, D. M., & Mason, A. K. A computer program for generating inherent corrective maintenance workload times (Tech Rep. No. 50). University of Southern California: Behavioral Technology Laboratories, November 1966.

Siegel, A. I., & Wolf, J. J. Man-machine simulation models. New York: Wiley, 1969.

Strieb, M. I., Glenn, F. A., & Wherry, R. J. The human operator simulator: An overview. Presented at the NATO AGARD Conference on Manned Systems Design, Freiburg, West Germany, September 1980.

Towne, D. M. ARMAN--a computer system for applying MTM. Proceedings Conference of MTM Applications, Los Angeles, 1968.

Towne, D. M. New software program aids work measurement of clerical operations. Industrial Engineering, 1980, 12(8).

Towne, D. M., Fehling, M. R., & Bond, N. A. Design for the maintainer: Projecting maintenance performance from design characteristics (Tech Rep. No. 95). University of Southern California: Behavioral Technology Laboratories, July 1981.

Human Factors, System Safety, and Aviation Maintenance

M. Pianka

Naval Air Test Center
Patuxent River, Maryland

Safety in today's world has taken on new meaning. To the professional, safety is no longer the simplistic "freedom from hazard for man." Instead, a new and much broader definition has come into use. Now, safety means "freedom from the people/equipment/material/environment interactions that result in injury to personnel, damage to the system, time loss or any downgrading of the mission objectives." This broadened scope of safety actually improves the overall protection of the individual when compared to the previous one.

The improved definition does not restrict the safety effort to man alone, rather it embodies the system within which man operates. When one considers this system, any loss of any attributes of the system becomes the main issue. As such, loss control then becomes the goal of safety, whether it is the preservation of human/equipment/material or environmental assets.

Another very important point to bear in mind about preventing loss is that losses (or "accidents") are not necessarily time based, i.e., they do not always suddenly occur as in a plane crash or a forest fire. Long-term exposure to a variety of energy sources may lead to unacceptable losses. On the human side, consider the health hazards of exposure to cotton fibers, coal dust, asbestos, vibration, high noise levels, etc. The courts have concluded that these injuries are "accidents" if there was sufficient knowledge available on the long-term effects. Consider the slow degradation of our planet's ecology and natural resources as examples of long-term losses that need to be controlled.

Losses occur as a result of some sort of energy, be it mechanical, chemical, electrical, or whatever. To minimize losses, one has to identify, analyze, and control these energies. For instance, consider fire. The three things that generally lead to a fire are fuel, oxygen, and an ignition source. Removing any one will stop the fire from starting or, if started, put it out. Removal of the risk of fire implies preplanning and that is precisely what loss control is all about, thinking ahead. There will always be situations where the risk cannot be completely removed. In these situations, a conscious decision has to be made to accept this risk. In the case of fire,

for example, risk acceptance may hinge on adequate fire extinguishing facilities being available. Corrosion is very similar to fire. After all, what is fire but a very rapid corrosion. Loss control due to corrosion can be tackled in a similar fashion.

There are two basic premises in loss control: (a) the incidents that downgrade the system's capability are caused; they do not just happen, and (b) these causes can be determined and controlled.

The four sources for these causes are given in the definition. They are: (1) people, (2) equipment, (3) material, and (4) environment. Seldom does any one act alone to cause an incident.

People need to have proper training and leadership in order to be able to do their job with pride. They also need good equipment that is designed properly, available with the proper tools to repair, operate, and maintain it. The material that has to be worked with may be toxic or otherwise dangerous, so proper safeguards must be taught, available and utilized. Lastly, the environment must be benign or the workers must be protected from excessive noise, wind, moisture, heat, cold, etc.

The above examples are but a few of the myriad of possible variations available in each broad causal category. For example, people vary in intelligence, perceptual ability, physiology, moods, emotions, etc. After all is considered, the permutations and combinations possible are astronomical. Yet any one of these is the rare occurrence that may result in a catastrophic loss of life or property. In some cases, we may even be talking about the eventual end of life on our planet. The goal of loss control professionals is to attempt to preconceive the worst of the consequences and then find some means of controlling or outright avoiding them. Their success is measured in lives and dollars, yet it is difficult to quantify that which has never been. As more and more systems have loss control theory applied to their development, comparisons will be able to be made to illustrate these savings in a more understandable form.

Techniques for Hazard Identification

The greatest difficulty with loss control application is the identification of hazards. You cannot control or eliminate what you do not recognize. Consequently, many different types of checklists have been developed to assist in the identification of possible energy sources (see Tables 1 and 2). Checklists are only intended to provide a starting point since most systems incorporate unique sources of energy problems.

When using any checklist, it is important to realize failures may occur at different points in the development of a new system. That is, during the engineering phase, common failures may occur due to the design or the construction of the system. Design failures may be further subdivided to include functional deficiencies such as undetected hazards or inadequate controls, and realization faults found after the design is complete such as inadequate materials, operational deficiencies, channel dependency, etc. Construction failures may be due to either manufacturing or installation. These types of failures generally result from inadequate inspections, quality control, testing, standards, etc.

During the operational phase, failures may be caused by either procedural or environmental considerations. Procedural failures may result from either maintenance or normal operations. Maintenance errors generally result from lack of precision in repairs, calibrations, testing, or procedures, whereas operations failures result from human error (either operator or supervisor), inadequate procedures, or communication breakdowns.

Environmental failures relate more directly to energy sources and are thus easier to prepare against. There are the normal energy extremes encountered such as shock, temperature, pressure, vibration, humidity, etc., as well as the energy extremes from external events that may be encountered such as fire, flood, explosions, earthquakes, radiation, etc.

Checklists that are used and annotated can be filed and represent the nucleus of a corporate mind relative to the developing systems as well as similar future systems. They also provide an invaluable source to return to when unexpected failures occur, thereby becoming a very expensive lesson-learned file. Any failure of any system should be recorded and used to prevent similar failures in the future on new systems.

Table 1

Energy Source Checklist

1.	Fuels	12.	Electrical Generators
2.	Propellants	13.	Electromagnetic Radiation
3.	Initiators	14.	Radioactive Energy Sources
4.	Explosive Charges	15.	Falling Objects
5.	Charged Electrical Capacitors	16.	Catapulted Objects
6.	Storage Batteries	17.	Heating Devices
7.	Static Electrical Charges	18.	Pumps, Blowers, Fans
8.	Pressure Containers	19.	Rotating Machinery
9.	Spring-loaded Devices	20.	Actuating Devices
10.	Suspension Systems	21.	Nuclear
11.	Gas Generators	22.	Cryogenics

Table 2

General Hazard Source Checklist

1. Acceleration	11. Oxidation
2. Contamination	12. Pressure
3. Corrosion	High
4. Chemical Dissociation	Low
5. Electrical	Rapid Changes
Shock	13. Radiation
Thermal	Thermal
Inadvertent Activation	Electromagnetic
Power Source Failure	Ionizing
Electromagnetic Radiation	Ultraviolet
6. Explosion	14. Chemical Replacement
7. Fire	15. Shock (Mechanical)
8. Heat and Temperature	16. Stress Concentrations
High Temperature	17. Stress Reversals
Low Temperature	18. Structural Damage or Failure
Temperature Variations	19. Toxicity
9. Leakage	20. Vibration and Noise
10. Moisture	21. Weather and Environment
High Humidity	
Low Humidity	

When a new system is first conceived is the time to begin the first hazard analysis. This initial hazard analysis is called the Preliminary Hazard Analysis (PHA) and should represent an attempt to define all of the energy sources inherent within the proposed design. Knowledge of these hazards can help the engineering staff in determining design characteristics that help to minimize potential hazards. As the system matures and becomes more defined by the design, the PHA must be updated to encompass the new definitions. An effective PHA will have its impact felt throughout the life-cycle of any product. An example format for performing a PHA is given in Figure 1. The columnar format is used because a given portion of the proposed system may have more than one failure mode, with each mode having a different probability of occurrence with varying effects on the overall system. These differing effects may in turn lead to different degrees of hazard severity. Obviously, different failure modes and effects require different types of controls to eliminate or reduce the probability of a hazard occurrence.

The PHA is the first hazard analysis performed, and as such, is very broad and gross. Other hazard analyses are performed at different parts of the life-cycle as more detailed information becomes available. If the PHA was properly done, these other hazard analyses will be considerably easier. Other hazard analyses consist of a close look at each subsystem and how it marries to the whole, the effects of radiation, the effects of electromagnetic pulses, and other hazards associated with the normal operation and maintenance of the system. Although all of these hazard analyses are important, the Maintenance Hazard Analysis (MHA) will be used as an example since it is of particular interest to the reader. As can be seen from Figure 2, the MHA is similar to the PHA insofar as the columnar format is concerned. Note that a MHA is performed for each subsystem. This assures that all required maintenance hazards can be identified and accounted for.

The MHA is started early in the validation phase of the life-cycle prior to the first design review. It is updated as system design solidifies and should be reviewed for each modification, redesign, or engineering change that occurs after its completion.

The analysis uses information from engineering design data, descriptive data of support and test equipment, and actual hardware inspection. For example, the analyst must constantly consider the rolling and pitching deck environment of ships when assessing hazards associated with the maintenance of a waterborne system. Human factors must be considered with regard to anthropometry, strength, educational levels, cognitive loadings, etc. In addition, maintenance tasks must consider lifting requirements, physical support, exposure to high voltages, release of pressures, fluids and/or gases, exposure to microwaves or X rays, disposal of toxic substances, and general interference by or with flexible or fixed cables, piping, or similar equipment subject to damage by abrasion or impact.

The MHA form given in Figure 2 is completed by carrying out the following steps:

Step 1. <u>General</u> - The title block data identifies the system and subsystem being analyzed, maintenance level (organization or intermediate) data, and other self-explanatory information.

Program ____ System ____ Subsystem ____ Revision ____ Rev. Date ____	Preliminary Hazard Analysis (PHA)	Completed By ____ Date Started ____ Date Completed ____ Page ____ of ____ Pages

Item No.	Nomenclature and Part No.	Operating Mode	Failure Mode	Estimated Probability	Failure Effects	Hazard Description	Hazard Class.	Recommended Control	Amplifying Remarks (Include Verification)
1	2	3	4*	5**	6	7	8	9	10

*Failure mode includes effects of human error, normal and abnormal environments, design deficiencies, incompatibility

**Enter one of the following:
- o Low - Low or remote probability
- o Medium - 0.001 to 0.0001 probability
- o High - 0.001 probability
- o UNK - Unknown probability

Figure 1. Example format for PHA.

System ______ Subsystem ______		Maintenance Hazard Analysis (MHA)			Analyst ______ Sheet ___ of ___ Maintenance Level ______ Date ______	
Equipment 1	Maintenance Type 2	Maintenance Function 3	Hazard 4	Hazard Class 5	Safety Feature or Recommendation 6	Remarks/ Recommendation 7

Figure 2. Example format for MHA.

Step 2. Column 1 - Equipment - This column divides the analysis into sections. The listing should be ordered by the system Work Breakdown Structure. The entry should show the major assembly, such as wheel breaks, in the landing gear subsystem or elevators in the flight control subsystem, on which the maintenance is performed.

Step 3. Column 2 - Maintenance Type - This entry identifies the general maintenance type being analyzed. Entries may include such types as preventive maintenance, corrective maintenance, fault isolation, etc.

Step 4. Column 3 - Maintenance Function - In this column, define the single function being considered such as lubricate, adjust, calibrate, test, isolate fault, or remove or replace an identified component.

Step 5. Column 4 - Hazard - The hazard associated with the function and tasks identified by columns 2 and 3 is identified here. Typical entries include high voltages, moving parts, toxic substances, inadequate support, etc.

Step 6. Column 5 - Hazard Classification - Hazards can be classified according to their severity and probability of occurrence. For example, Figure 3 shows a detailed breakdown of the most severe category (i.e., category I) utilized by the Department of Defense. As can be seen, severity is based on the number of lives or type of equipment at risk. Category II hazards are considered "critical" and may lead to severe injury or illness and/or major damage to a system. Category III hazards are "marginal" involving minor injury or illness and/or minor damage to a system. Category IV hazards are "negligible" meaning there is no risk of injury, illness or damage. Obviously, each level of hazard except category IV has an unacceptable rate of occurrence at which point measures must be taken to prevent that occurrence. Figure 4 shows the areas of acceptable risk based on probability of occurrence for each hazard category.

Step 7. Column 6 - Safety Features or Recommendations - The safety features that have been incorporated in the equipment design or maintenance plans and facilities are listed in this column. Add any recommended controls to prevent an accident if already-incorporated safety features are deemed inadequate.

Step 8. Column 7 - Remarks - The remarks column identifies the category I and II hazards in column 5 that are not eliminated by safety features. This is where recommended corrective action such as design changes, safety or warning devices, warnings signs and personnel training are made.

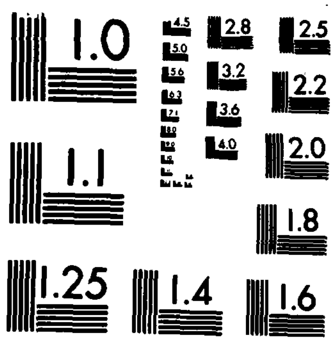
The MHA is most often used to develop requirements for cautions, warnings, and emergency procedures for inclusion into maintenance manuals and plans.

Techniques for Hazard Analysis

This section will introduce the reader to various hazard analysis techniques. Far more comprehensive expositions on these techniques are available elsewhere (e.g., D. B. Brown, 1976).

AD-A160 934 PROCEEDINGS OF A CONFERENCE ON A COMPREHENSIVE TECHNICAL REVIEW OF HUMAN (U) NAVAL AIR DEVELOPMENT CENTER WARMINSTER PA D K MCBRIDE ET AL 11 MAR 82 2/3

UNCLASSIFIED SBI-AD-F630 624 F/G 5/5 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

CATEGORY I LEGEND

CATEGORY	LIVES	SMALL SYSTEM (AIRCRAFT)	LARGE SYSTEM (SHIPS)
I A	1 - 5	Fighter/Attack	---
I B	6 - 10	Patrol/Small Transport	---
I C	11 - 100	Large Troop Transport	Destroyer/Submarine
I D	101 - 1000	---	Carrier Battleship/Atomic Plant

Figure 3. Hazard severity.

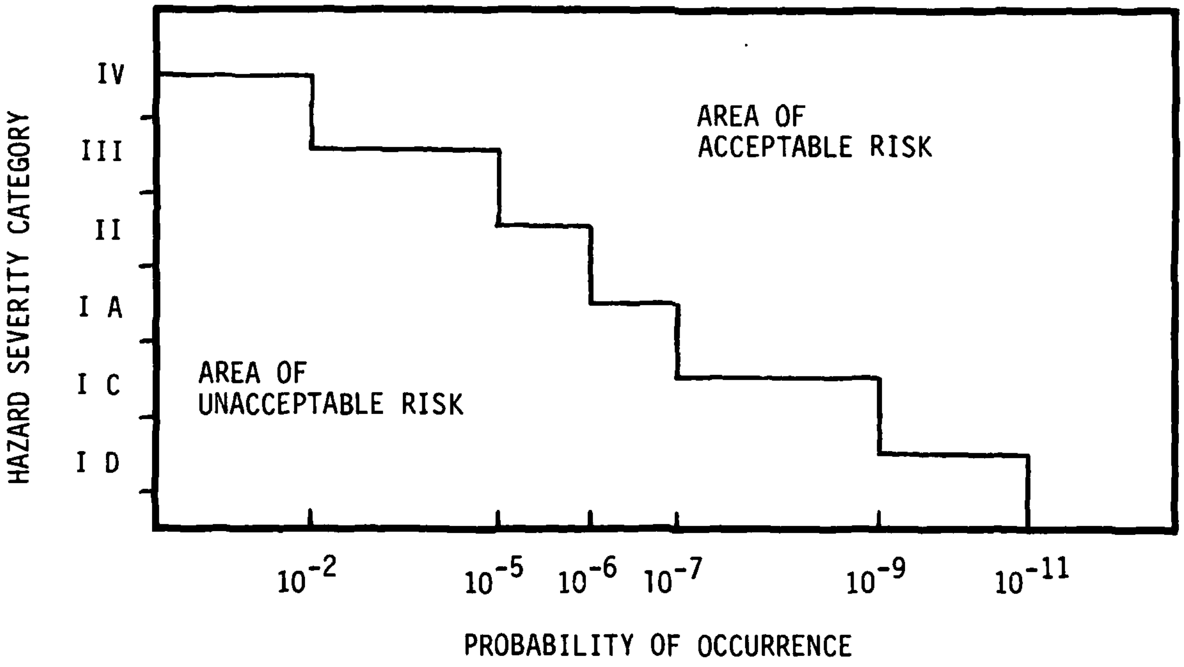


Figure 4. Hazard probability.

A basic concern of the human factors specialist working in safety is the ability to assess the impact of operator error within the system being investigated. The techniques to be described here allow for the inclusion of human error.

In order to work with human error, one must first define what types of human error are being considered. If you consider human error as a behavior, then it follows that errors can result from intentional, unintentional or omitted acts. In any case, the errors may be caused by errors in the inputting, mediation or outputting of information. Errors due to input consist of reading dials or scales, labels, etc. Confusion of instructions or difficulty of interpretation are considered input problems. Mediating errors result from such things as failures in identification or recognition. Output errors are response oriented such as movement of levers, switches, oral or written responses, etc.

The point of breaking down the possible areas where human errors may occur is to illustrate that, of the possible nine combinations between the acts and the processes, each one has a distinct probability of occurrence. The problem is to find out what that probability is and to determine the acceptability of the associated risk.

There is a method developed by Sandia Corporation known as the Technique for Human Error Rate Prediction (THERP) that can be useful in making these decisions. THERP presumes knowledge of basic error rates (BER). Table 3 is an example of some basic error rates for humans. Although there is a large list of such error rates available, the variability between operators and working conditions require caution in its use. Researchers are working to improve both the quantity and quality of such data.

The THERP process begins with the analyst picking a specific high cost failure with human error in the chain of antecedent events. Then, the BER for each possible operator error is assigned and the total probability of failure is calculated. If the probability of occurrence is too high to accept the risk, the analyst then goes back to look at where improvements can be made to reduce human error rates, thereby reducing the overall failure rate. This procedure can be repeated as often as necessary until the risk is acceptable.

Where does one find those critical areas where human errors can contribute to the overall catastrophic failure? PHAs and the associated columnar type analyses deal more with hardware than with human error. One of the most useful techniques available to an analyst that can incorporate human error is the Fault Tree Analysis (FTA). The principles of FTA have been around for centuries in the form of logic trees and, as such, are actually representative of symbolic logic diagrams.

Fault trees are useful to a point, beyond which they can be counterproductive. A primary rule to follow concerning fault trees is that they should only be done on specific undesired events that have been identified by other hazard analyses. The reason for this is that properly performed FTAs are very time-consuming (hence, expensive) and quite often become too large to be meaningful. Another associated problem is that the

Table 3

Representative Human Error Rates*

Task Element			
Action	Object	Error	BER**
Observe	Chart	Inappropriate switch actuation	1128
Read	Gauge	Incorrectly read	5000
Read	Instructions	Procedural error	64500
Connect	Hose	Improperly connected	4700
Torque	Fluid lines	Incorrectly torqued	104
Tighten	Nuts, bolts	Not tightened	4800
Install	Nuts, bolts	Not installed	600
Install	O-ring	Improperly installed	66700
Solder	Connectors	Improper solder joint	6460
Assemble	Connector	Bent pins	1500
Assemble	Connectors	Omitted parts	1000
Close	Valve	Not closed properly	1800
Adjust	Mechanical linkage	Improper adjustment	16700
Install	Line orifice	Wrong size installed	5000
Machine	Valve port	Wrong size drilled and tapped	2083

(From NSC Rpt 2M57009 by J. L. Recht)

*These data should not be used for computational purposes without additional background information - specifically, under what conditions these rates can be expected to be valid and the probable error in each rate.

**Basic error rate (errors per million operations).

final determination concerning the undesired event's occurrence is only as realistic as the assumptions and probabilities assigned within the logic tree itself.

A FTA is a deductive analytical means to identify all failure modes contributing to the potential occurrence of a given top undesirable event. It displays all the necessary and sufficient failure modes which cause the top event. The fault tree analysis can be completed in either a qualitative or quantitative form. Every analysis begins qualitatively and is most valuable at this stage. This is where hazards which might otherwise have been overlooked are recognized and can be addressed.

Quantification of a FTA is simply a matter of assigning probability levels to all the basic events. These probability levels, in turn, are used to calculate the total probability that the undesired top event may occur (as will be shown later).

Fault trees are constructed using combinations of the symbols given in Figure 5. These are not exhaustive but represent the most commonly used symbols that allow for ease of quantification. Figure 6 is an example of a simple fault tree showing the various levels of analysis using different gates. Each alpha character represents a level or segment of analysis. Each event within a fault tree occurs in either of two states, i.e., failed or not failed, and each condition has a probability associated with it such that:

$$P(S) + P(F) = 1$$

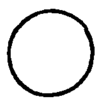
Where P(S) is the probability of success and P(F) is the probability of failure.

Each level of a fault tree will have a probability of success or failure associated with it. For example, in Figure 6, Event E2 has a probability of failure based on the failure rates of E21 <u>or</u> E22 <u>or</u> E23 <u>or</u> E24, whereas Event D2 has a probability of failure based on the failure rates of Events E1 <u>and</u> E2.

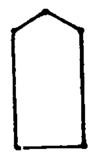
To further illustrate the analysis technique a simplistic example will be developed. Assume a top undesirable event of a hot start on a jet engine and the simplified logic tree as depicted in Figure 7. Each event within the logic tree has a specific meaning. Table 4 identifies these various meanings. Note that events C11 and C13 are the same as events C21 and B22 respectively.

The problem is to determine the probability of a hot start occurring. Table 5 gives the assumed probabilities for each of the events. In the real world, these probabilities would come from research data and experience. Where nothing is available, an educated estimate is used. If the event without a quantitative probability is critical to the survival of the system, a collective estimate from several experienced professionals should be used. Although this technique may seem less than scientific, one should bear in mind that in the absence of an alternative, anything is better than nothing. This technique then allows the analyst to change probability levels to adjust the probability of the outcome until an acceptable level is reached (note the

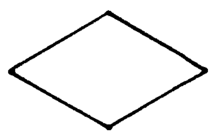
The rectangle identifies an event that normally results from the combination of fault events through the input logic gates. The top fault tree event is always depicted with a rectangle.



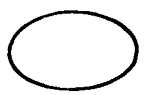
The circle describes a basic fault event that requires no further development.



The house indicates an event that must occur due to normal operating conditions in the system. The probability of occurrence for this event is the reliability of the component.

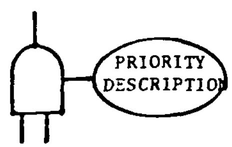


The diamond describes a fault event that is basic to the fault tree. It indicates that further breakdown could be done if required but the probability of occurrence is so low as to not warrent further analysis.

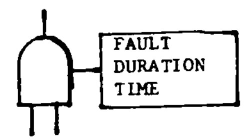


The oval is used to describe a conditional event.

This is the basic 'AND' gate whereby the coexistence of all input events is required to produce the output event.

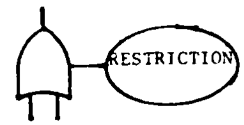


The 'PRIORITY AND' gate performs the same logic function as 'AND' gates with the conditional stipulation that sequence as well as co-existence is required.

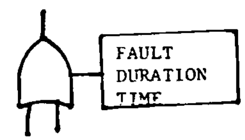


The 'CONSTANT FAULT DURATION AND' gate is the same as an 'AND' gate except that the fault duration time of the output is not dependent on the inputs.

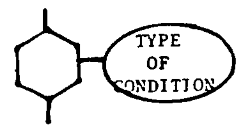
This is the basic 'OR' gate whereby the output event will exist is one and/or more of the input events exist.



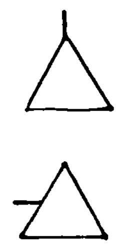
The 'EXCLUSIVE OR' gate functions the same as an 'OR' gate with the restriction that either one input or the other exists but not both.



The 'CONSTANT FAULT DURATION TIME OR' gate functions the same as an 'OR' gate except that the fault duration time of the output is not dependent on the inputs.



The 'GENERAL INHIBIT' gate describes a causal relationship between one fault and another. The input event directly produces the output event if the indicated condition is satisfied. It is treated as an 'AND' gate.



Triangles are transfer functions. A line from the apex denotes a transfer into the logic tree wheras a line from the side indicates a transfer out.

Figure 5. Common symbols for fault tree elements.

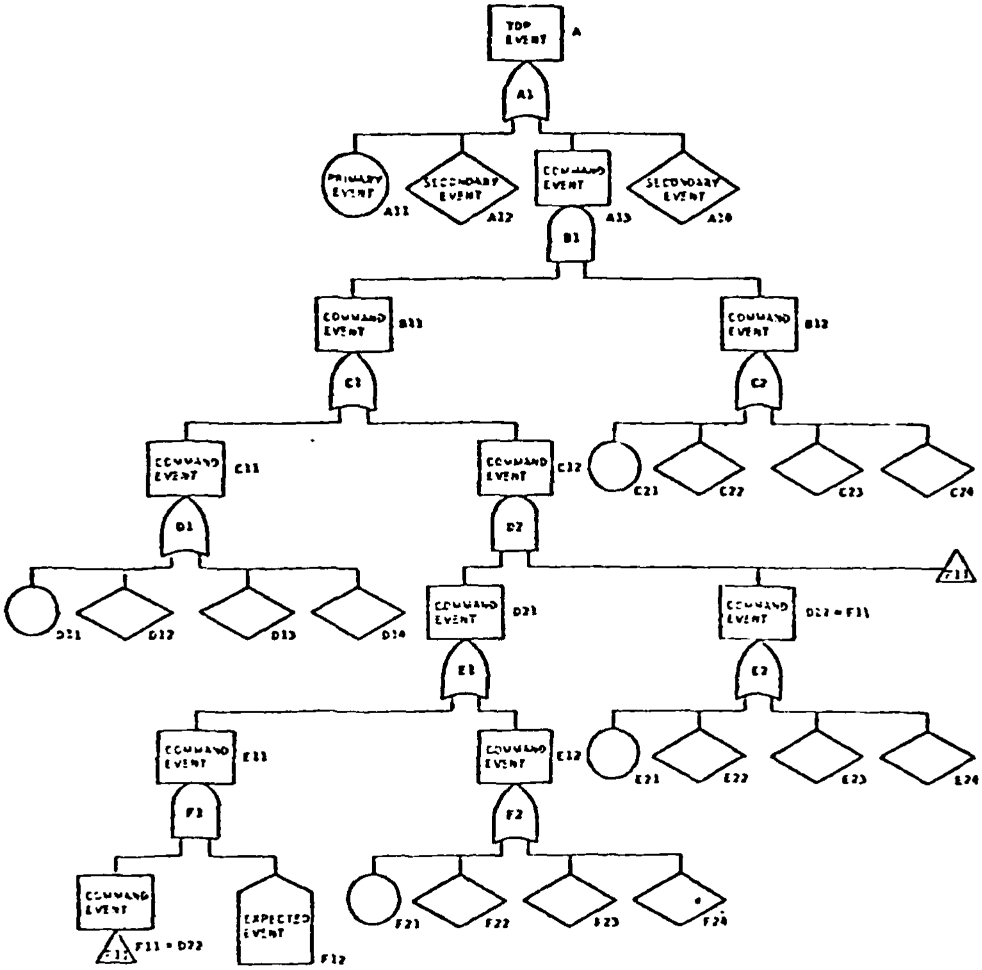


Figure 6. Example of six level fault tree.

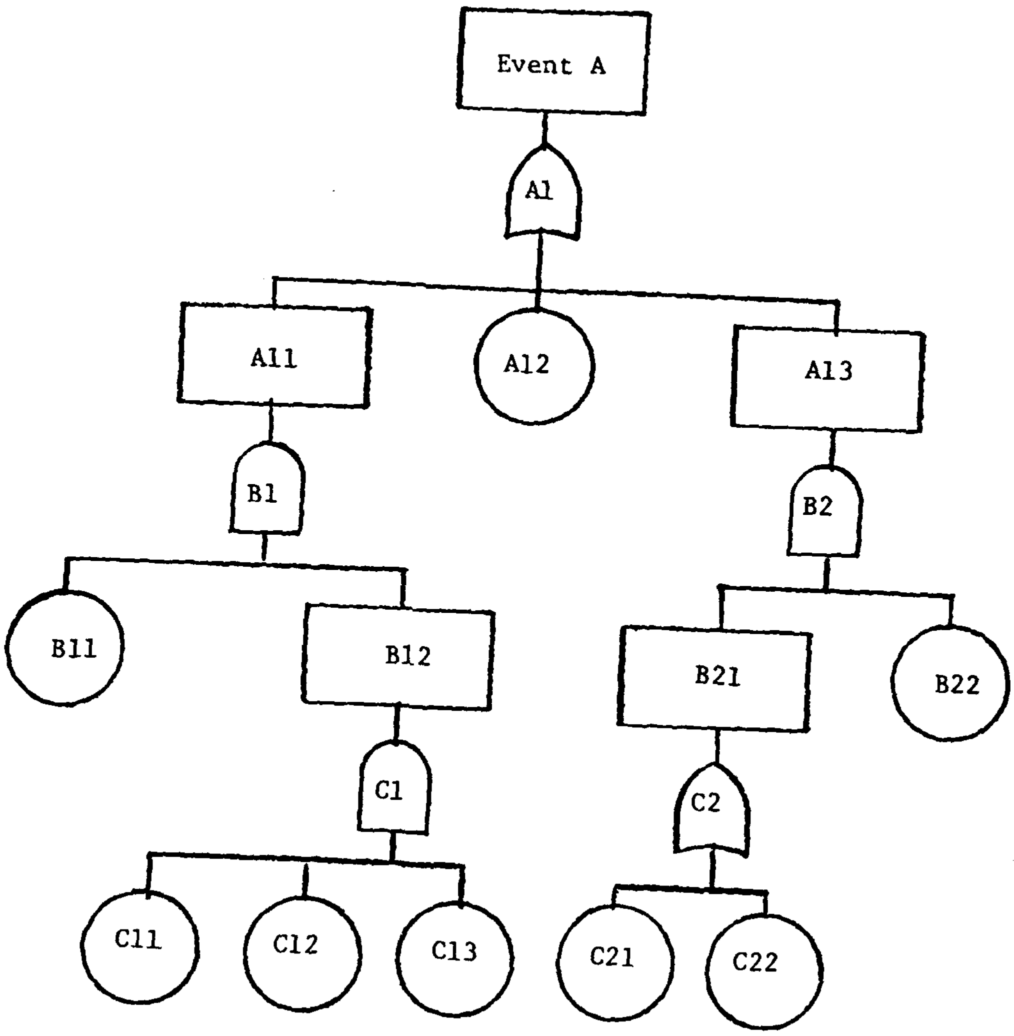


Figure 7. Simplistic fault tree.

Table 4

Descriptive Meanings for Figure 7

A:	Hot start on jet engine
A11:	Wrong fuel
A12:	Too much fuel to engine
A13:	Residual fuel in engine
B11:	Human error, wrong fuel truck
C11 = C21:	Human error, poor pre/post flight
C12:	Wind from rear
C13 = B22:	Blocked fuel drain
C22:	Quick turnaround required

Table 5

Given Probabilities for Events Given in Figure 7

Probabilities
A11: .005
B11: .001
C11 = C21: 0.25
C13 = B22: .005
C22 = 0.2
C12 = .01

similarity to the THERP process). Once the probability levels have been decided, the engineers can decide to reach the proposed reliability levels or alter procedures, etc., to reach the desired end point.

To calculate the overall probability of Event T, it is useful to modify our logic tree as can be seen in Figure 8. This is done strictly to allow for easier algebraic manipulation.

The process for determining Event T's probability begins from the bottom of the logic tree and works upward. Each branch is done separately; that is, first we calculate Y_2 then Y_1; and X_2 then X_1. Once we have calculated the probability of both Y, and X, then we can calculate the probability of Event T.

To calculate an event governed by an 'OR' gate, the following formula is used:

$$P_O = 1 - \Pi^n{}_{i=1} (1 - q_i)$$

Where $\underline{q_i}$ is the probability of the i^{th} causal event and n is the number of parallel branches. The symbol II is a product of terms symbol. For events governed by an 'AND' gate, the probability of occurrence is given by:

$$P_A = \Pi^n{}_{i=1} q_i$$

Substituting the given probabilities from Figure 8 into the appropriate formula, event $Y_2 = .4$, $Y_1 = .002$, $X_2 = 1.25 \times 10^{-5}$ and $X_1 = 1.25 \times 10^{-8}$. Event T can now be calculated using the P_O formula.

$$\text{Event T} = 1 - \underset{Y_1}{(1 - .002)}\underset{A}{(1 - .005)}\underset{X_1}{(1 - 1.25 \times 10^{-8})}$$

So Event T = .007

This shows that the probability of a hot start is approximately 1 out of 100 (actually 7 out of 1000).

If this frequency of occurrence is too high, then the next thing to determine is where the most payoff can be made altering probability levels. There are several techniques to determine this. All the techniques basically do the same thing, i.e., determine the minimal cut sets within the logic system.

A minimal cut set can be defined as the smallest group of basic end events whose collective occurrence assures the occurrence of the top event. The basic end events may be hardware failures or human errors. A minimal cut set may not contain another cut set since that would imply that the former was not minimal. The number of events in a minimal cut set determines the number of failure points in the system. For example, a minimal cut set of one is a single point failure, two a dual point and so forth.

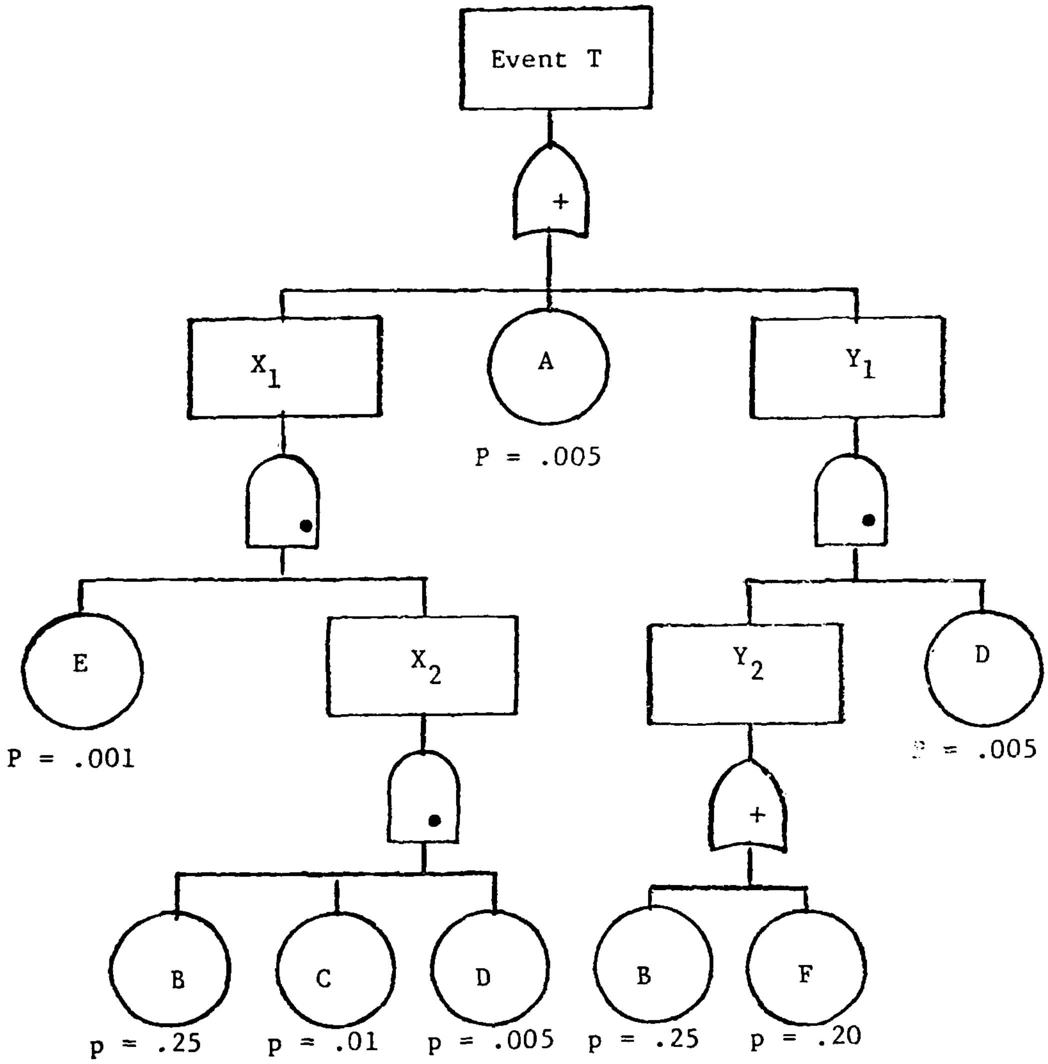


Figure 8. Modified fault tree with given probabilities.

The first technique to determine minimal cut sets will be the use of symbolic logic and Boolean Algebra. Table 6 presents a list of Boolean Algebra postulates. When writing a Boolean expression, an 'OR' gate is additive (note the + sign in the 'OR' gate in Figure 8) and an 'AND' gate is multiplicative (note the o in the 'AND' gate in Figure 8). Using the modified fault tree in Figure 8, the Boolean expression for the logic system will be developed.

$$T = X_1 + A + Y_1$$

$$\text{Where } X_1 = E(X_2)$$

$$\text{and } X_2 = BCD$$

$$\text{so } X_1 = E(BCD) \text{ or } EBCD$$

$$\text{also } Y_1 = Y_2(D)$$

$$\text{Where } Y_2 = B + F$$

$$\text{so } Y_1 = (B + F)D \text{ or } BD + FD$$

$$\text{Therefore } T = EBCD + A + BD + FD$$

When working with Boolean Algebra it is useful to apply Rule 11 from Table 6 and keep alphabetical order.

$$\text{So } T = BCDE + A + BD + DF$$

Now factoring BD we get:

$$T = BD(CE + 1) + A + DF$$

$$\text{and } CE + 1 = 1 \text{ (Rule 5)}$$

$$\text{so } T = BD + A + DF \text{ or } T = A + BD + DF$$

These represent the furthest reduction possible and as such become the minimal cut sets for this logic tree. Events C and E are not considered because before conditions to cause them have occurred, events B and D have already occurred. Remember that BCDE includes BD so it is not a minimal cut set.

Another method to determine cut sets is to use a chart. Table 7 shows the process. Events under 'AND' gates are placed horizontally and those governed by 'OR' gates are placed vertically until all end events have been placed into the chart. Once this chart has been completed, then minimal cut sets can be determined by assuring that no cut set is used containing a smaller cut set. The chart process further illustrates the number of failure points within the logic tree. This does not appear too important when using a simplistic logic tree as the one given, but for more complex problems, such information takes on new meaning.

Table 6

Boolean Algebra Postulates

1.	$(A + 0) = A$
2.	$A(1) = A$
3.	$AA = A$
4.	$A + A = A$
5.	$A + 1 = 1$
6.	$A(0) = 0$
7.	$\overline{\overline{A}} = A$
8.	$(A + \overline{A}) = 1$
9.	$A(\overline{A}) = 0$
10.	$A + B = B + A$
11.	$AB = BA$
12.	$A + (B + C) = (A + B) + C$
13.	$A(B + C) = AB + AC$
14.	$A + AB = A$
15.	$A(A + B) = A$
16.	$\overline{AB} = (\overline{A} + \overline{B})$
17.	$\overline{A}\ \overline{B} = (\overline{A + B})$
18.	$(A + \overline{A}B) = A + B$
19.	$A(\overline{A} + B) = AB$
20.	$AB + A\overline{B} = A$
21.	$(A + B)(A + C) = A + BC$
22.	$(A + C)(A + C) = A$

Table 7

Determining Cut Sets from Chart Method

Size of Cut Sets →

AND gates

No. of Cut Sets ↓ OR gates

(A)

A			
X_1			
Y_1			

(B)

A			
E	X_2		
Y_2	D		

(C)

A			
E	B	C	D
B	D		
F	D		

The fact that event A is a single point failure makes it most important since its failure alone will cause the top event. However, if for instance X_1 or Y_1 were highly probable given the probability levels of their branch events, event A may not be the most important point to try to change the system. Event D occurs in two places, that is in both of the two point minimal cut sets. It is obvious that by changing the probability of event D one would have a greater impact on the whole system than by changing events B or F even though event B also occurs twice. Event B only occurs in one minimal cut set.

It is important to stress that when using Boolean Algebra, the alpha characters represent events and that the manipulation of these events is a means of determining those that tend to be most important. The analyst can then go back from the alpha characters to the events themselves to see what the results are implying and to determine whether or not further reduction in the probability of failure can be undertaken.

Techniques for Hazard Control

The title of this section is misleading as techniques will not be addressed as such, rather, the philosophy of hazard control will be discussed. Once a hazard has been identified and analyzed, something should be done about it. The techniques described in the analysis section regarding the identification of critical failure points apply equally here. The most critical failures need to be addressed first in a progression to the least critical (see Figure 4).

The most obvious method of controlling a hazard is to eliminate it entirely. This is generally a job for a design engineer and may actually entail a major restructuring or modification of the system. This, in turn, has a certain cost, not only in terms of dollars, but also in terms of time, i.e., readiness. If the hazard cannot be eliminated by a design change for some reason, then one must seek some sort of reduction in the hazard. This can be accomplished by design changes that either reduce the severity should the hazard occur, reduce the probability of its occurrence, or by a combination of the two.

Design changes are not always possible or desirable. In some instances, design changes may actually reduce the effectiveness of the system to a point where the system would not perform its assigned mission. Therefore, in lieu of design changes, hazards may be reduced by using either safety or warning devices. Safety devices are such things as interlocks which inhibit execution in the wrong sequence, whereas warning devices may be a sound or a flashing light that signals an unsafe condition.

If the preceeding steps cannot be taken, or are taken but fail to eliminate or control the hazard enough, the last fall-back position is to alter the procedures that effect the hazard. Procedures may involve special protective equipment, special training or proficiency trainings, and cautions and/or warnings in technical publications.

The order of the steps given is also the order of their precedence. Each time it is necessary to step down from design to safety devices to warning devices to procedures, less control of the hazard is exercised. The decision to accept the hazard at a particular level is generally left up to the manufacturer or, in the case of the military, the program manager. After all attempts to eliminate or control the hazard have been applied, the final acceptance of risk is based on the need for the system and the mission that the system is to perform. Some systems such as rockets or other types of explosives are inherently hazardous but must be used if a strong defense is to be maintained.

Another point to consider is that there is seldom a completely safe system. Figure 9 illustrates this, showing that absolute safety is not possible because the cost of the countermeasures becomes infinite in theory. Not mentioned in the graph is the effect of the countermeasure on the performance or mission of the given system. The object of any manager is to find the point where optimal safety is reached because that maximizes the amount of safety available with minimum cost.

The cost of safety has been discussed several times. How does one calculate the cost of safety? Safety, after all, is not something that happens now, rather it is something that lies in the future. Not only is safety a future event, but if it works nothing happens. Considering the different steps that can be taken to improve safety, i.e., reduce or eliminate a hazard, how can the most cost-effective technique be determined? Since safety is a future event that we want to invest in, the amount of time that the investment will work for us is important. The basic idea is that if we invest X amount of dollars now to incorporate a specific change in a system that has a life expectancy of N years, the overall savings in terms of dollars not lost due to accidents/mishaps will be worth the initial X amount of dollars. To figure out this problem we can turn to the economists for some of their computations. The series Present Worth Factor (PWF) computes a future value of a series of investments over time and is given by:

$$(PW - i - n) = \frac{(1 + i)^n - 1}{i(1 + i)^n}$$

Where i = opportunity cost

and n = number of periods

The opportunity cost is actually the same as the interest except we are redefining it to mean that it is the cost incurred should you fail to select the improved safety proposal.

For example, consider Figure 10. Here, a system with a life expectancy of eight years is depicted. At time 0 an investment in dollars is made which has an effect in two years and reduces the overall costs per year for six years from level b to level a. Was the initial investment worth it?

An example with numbers will help illustrate the utility of this technique. Assume an engineering change proposal (ECP) that costs $80,000 to install in a system and has a presumed life expectancy of seven years. Based

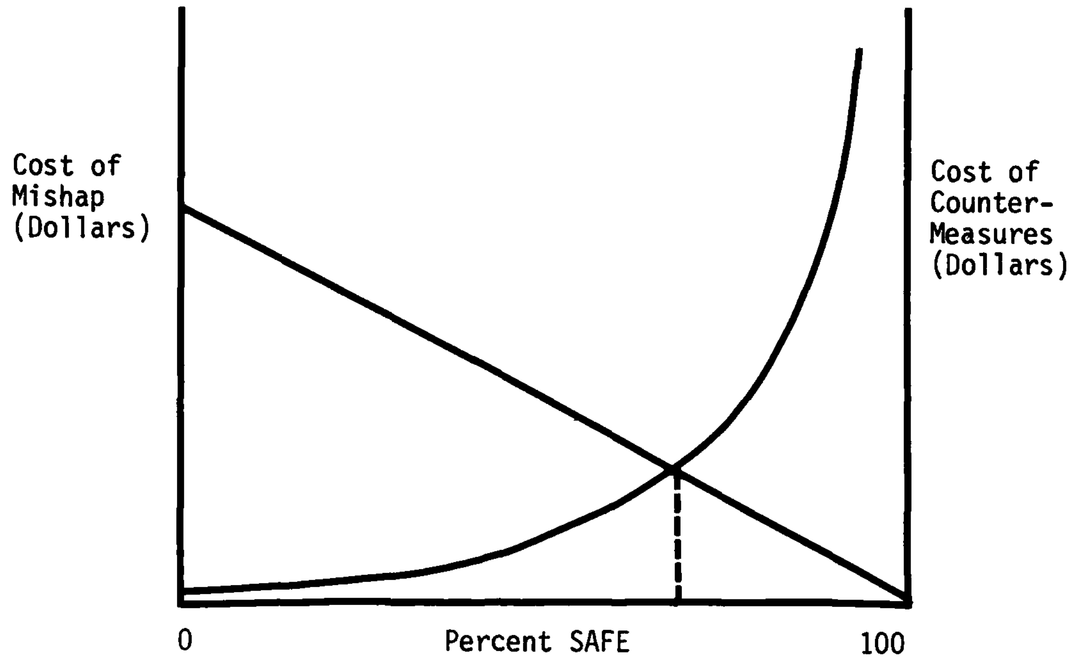


Figure 9. Optimum safety.

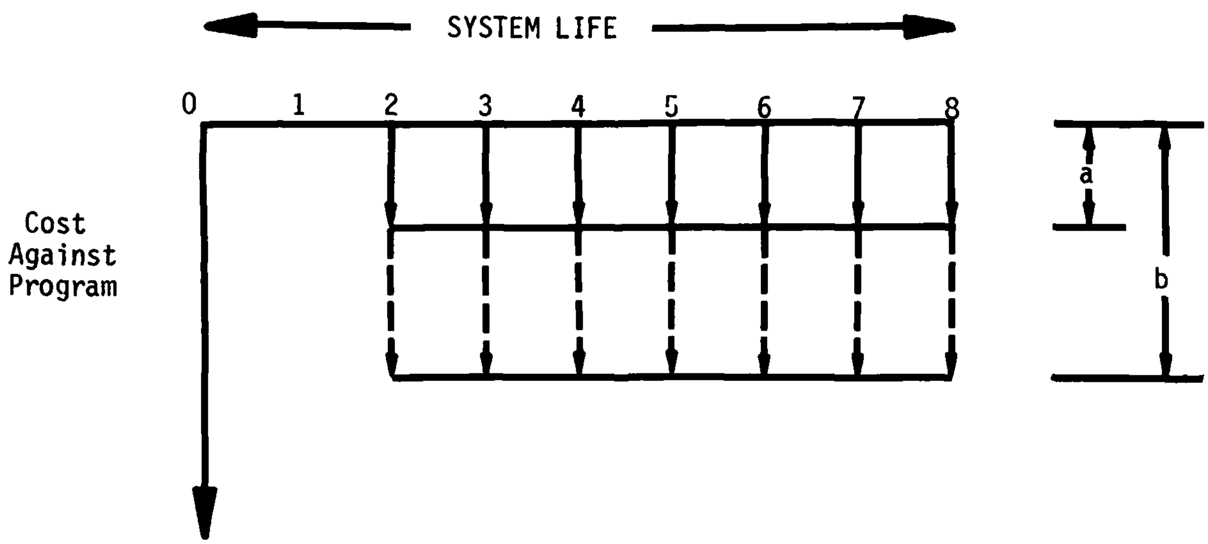


Figure 10. Diagram of cost savings.

on prior experience, our engineers estimate that without the change our annual loss would be about 70K and with the ECP, the loss would be about 50K per year. This represents a savings of 20K per year for seven years providing we invest 80K now. Management estimates that inflation (opportunity cost) will be about 10 percent during this period. So, what would be the value of 140K (20K/yr savings times seven years) deflated annually by 10 percent for seven years? The present worth factor over this period is:

$$(PW - .10 - 7) = \frac{(1 + .1)^{7} - 1}{.1(1 + .1)} 7 = 4.868$$

So 20K (4.868) equals \$97,360 and \$97,360 is greater than \$80,000 so we would save \$17,360 by making the change. In terms of dollars, the 80K investment is worth it.

However, if management saw their opportunity cost as 17 percent rather than 10 percent, the present worth factor would then be:

$$(PW - .17 - 7) = \frac{(1 + .17)^{7} - 1}{.17(1 + .17)} 7 = 3.92$$

So 20K (3.92) equals \$79,449 which is less than the 80K investment so it would not be profitable. The obvious flaw in these calculations is the accuracy of the estimates, not only of the future cost, but also what the opportunity cost might be. Future costs may very well skyrocket with even one law suit or unexpected recession's affect on inflation. The point is that given the best information available at the time, an assessment can be made as to whether or not a proposed expenditure is cost-effective. A little imagination will allow you to see other possible uses for this cost/benefit type of analysis. You could perform these computations for all variations of proposed means for hazard elimination and/or reduction to determine which one is the most cost-effective.

Once the most cost-effective proposal has been identified, the manager must decide if that is the proposal that should be implemented. One more consideration that must be taken into account before such a decision is made, is the social cost involved. There is no way to measure this in terms of dollars and cents. It consists of things such as public good will or company reputation. The most cost-effective procedure may also produce the most environmental pollution or be based on the fewest number of law suits due to consumer injury or death. Such social concerns may lead a manager to actually implement a more costly procedure simply to reduce the public's possible disfavor.

Maintenance and the Man

Systems that require maintenance require maintainers who are able to perform the required tasks. It is very difficult to describe the "average" maintainer. If we design a maintenance task for the 50th percentile person, does this mean that the 3rd and 98th percentile person can also perform the task? What about women? Obviously, the 50th percentile (average) man is not the same as the 50th percentile woman. In fact, the 50th percentile person does not exist, rather the phrase is used to represent the mean figures on a

number of variables such as height, weight, reach, strength, education, IQ, shoe size, etc. Any attribute you can conceive has a mean value which represents the "average" person. The fact that we have a selected population within the naval maintenance force confuses the problem somewhat since we have to know what the extreme values of our population are in order to define the "average" person.

The problem of designing a maintenance task for the "average" person is something that has yet to be mastered. As more and more information about the maintainer population is defined, the task becomes more realistic. It is doubtful if all the information will ever be known. There will always be some problems with exceptional situations that occur so infrequently as to not warrant any large expenditure of funds in attempting to identify them.

The fact that the "average" man is so elusive is only one of the problems. Another major consideration is the fact that human beings as a species have certain limits in their abilities. These include information processing, sensation, perception, and strength. One of the major tasks of design engineers is to develop tools which extend these limits and help to include the majority of the maintainer population. In order to do this, the engineers must know what these limits are so that their designs not only can extend them when necessary, but also so that the tools reach the minimum or maximum limits to begin with. After all, what good is a pair of pliers if a 5th percentile woman cannot squeeze them enough to perform the required function? It may be a matter of leverage or surface area that needs to be considered. The same applies to information processing. If a task is too hard to learn for a group of maintainers, perhaps either redesigning the task or rewriting the instructions on how to perform it would be beneficial.

Insuring that a maintainer can perform his required tasks as easily as is functionally possible is a large step in attempting to provide a safe working environment. When maintainers are performing their tasks, they are generally devoting most of their attention towards the proper execution and completion of the task and so expose themselves to hazards which would normally be avoided without much thought. The obvious example would be the troubleshooters trying to perform their duties on a flight deck during a night launch in marginal weather. It takes little imagination to see that the maintainer might be injured due to jet blasts or spinning propellers. The more their job has been designed to be easy, the more attention they will be able to devote to their surroundings. Thus, it is imperative that the design engineer design his system's maintenance functions to a worst case situation for the specified population of maintainers servicing that system. Anything less is failing to maximize safety and enhances the loss control for the total system which includes the hardware, operators, and maintainers.

Acknowledgement

The opinions expressed in this paper are those of the author and do not necessarily reflect the official policy of the United States Navy.

Design for Effective Maintenance

John C. Schmitt
Larry C. Lamb
John B. Mocharnuk

Harris Corporation
Melbourne, Florida

An overview of our Design for Effective Maintenance study (DEM) is presented in Table 1. The DEM study is a part of the NADC Design-for-Maintainers program. DEM attempted to do two things in particular. First, it was a feasibility study to determine whether useful data exists in the Naval Safety Center's data base. "Useful" is defined here as the extent to which data can result in what we term Effective Maintenance Design Features (EMDF), design principles concerning the human factors of maintainability.

Second, in a broader sense, we wished to develop a methodology applicable to Naval Safety Center and other data bases, a "model," which when applied to data will point to EMDFs. In the remainder of our presentation here, we wish to show that both of these objectives were met. That is, the Naval Safety Center data base certainly contains useful data, and we were able to develop a valid model of how to approach such data.

Our overview of the Naval Safety Center is presented in Table 2. Its stated mission is to preserve resources (both material and personnel) through the functions of detecting hazards, and then eliminating them through analysis and monitoring of corrective action. Analysis, of course, is the key, and so this function is implemented through the Accident and Mishap Data Base (AMD). The AMD provides for a very large amount of data to be recorded about each Naval Air mishap; these are coded by Safety Center personnel operating under OPNAVINST 3750.6M.

As we reviewed the data format and variable definitions of the AMD, we discovered 26 classes of variables relevant or potentially relevant to maintenance. By "variable classes," we mean to indicate that many variables have several versions, such as "First Involved Component," "Second Involved Component," etc. In all, there were 66 variables identified as relevant.

We also requested and obtained mishap narrative data up to 3000 characters long. All mishap records have a mishap narrative, but most are less than 200

words long. The narratives verbally describe the circumstances of the mishaps, and thus provide an invaluable opportunity to attempt to predict "situations" (narrative reports describing common maintenance problems) from objective data.

Finally, we found that the Naval Safety Center has indexed a subset of the AMD according to certain maintenance indicators and personnel causal factors where all members of the subfile have some maintenance component to the mishap. This file is termed the Maintenance Malpractice File, and we requested these records specifically rather than the entire AMD.

Table 1

Design for Effective Maintenance (DEM)

- Part of overall Design-for-Maintainers program
- Objectives:
  - Evaluate feasibility of using existing Naval Safety Center (NSC) data to extract Effective Maintenance Design Features (EMDFs)
  - Develop a methodology for extracting EMDFs from the NSC data base and other data bases

Table 2

Naval Safety Center

- Objective:
  - To preserve resources through hazard elimination
- Functions:
  - Hazard detection through individuals and commands with firsthand knowledge
  - Hazard elimination through analysis and monitoring of corrective actions
- Implementation: Accident and Mishap Data Base (AMD)
  - All mishaps coded at NSC (OPNAVINST 3750.6M)
  - 26 variable classes relevant to maintenance factors
  - Mishap narratives (up to 3000 characters)
  - Subset: Maintenance Malpractice File

Table 3 summarizes our study approach for DEM. We obtained the Maintenance Malpractice File for the five years 1977-1981 inclusive, for the 26 variable classes identified and the mishap narratives. This resulted in a

total of 5886 cases. We then looked at the univariate frequency distributions in a search for directions for further analysis. We had originally hoped to recode the data in such a way that multiple regression and its family of related techniques (factor, cluster and discriminant analysis) could be applied to the set. However, we found in looking at the distributions that the degree of missing data (i.e., virtually no case record had data entered for each variable) and the nominal-level nature of the data preclude this. Our later analyses, then, attempted to determine essentially the same things, associativity among variables, through nonparametric means, especially cross-tabulation.

In cross-tabulating, we set our goal as one of determining clusters of related systems and maintenance factors. This is a simple point, equivalent to saying that we would like to know what hardware (e.g., a specific component on a given aircraft) is associated with what maintenance/personnel "causes" of mishaps. This assumes that such incidents happening consistently contain useful information about potential human factors design flaws in terms of maintainability.

We then wished to develop a statistical model of the data out of which would fall cases with this presumed useful information. By "model," we originally conceived of regression models for selection; with the nonparametric schemes we adopted, "model" refers to the techniques we used to define a related cluster of cases. We then reviewed those cases' narratives ("folded back" the objective data on the subjective data) and attempted to derive EMDF hypotheses. From this point, we can outline ways to test those hypotheses which will result in true EMDFs.

Table 3

Study Approach

- Obtain Maintenance Malpractice File for five years (1977-1981)
- Frequency distributions of each variable for "clues," directions, hypotheses
- Cross-tabular analysis within and between variable classes for associativity of Systems and Maintenance factors
- Model for selection of cases for qualitative review
- EMDF hypotheses based on "foldback"
- Directions; future work

Table 4 and Figure 1 describe and show how our modeling approach proceeded. Beginning with a relatively amorphous data base (requiring substantial exploration to understand its structure and content), we sorted variables into those containing systems and maintenance information. We then

cross-tabulated these variables, and adopted numerous (iterative) criteria toward defining what a "large" cell was. When a large cell was found, we broke out the case narratives pertaining to that system-by-maintenance combination. Examining these and applying to them a process of subjective integration results in an EMDF hypothesis.

It is at this point that the scope of this present study ends. However, we feel that a microscopic examination of the hardware and maintenance environment bearing on the hypothesis can lead to validation of the EMDF. The steps of such a follow-through examination are described later and in Table 9.

Table 4

General Approach to Modeling

Elements
• Associative techniques
• Data reduction
• Foldback analysis
• Judgments/recommendations

Figure 2 depicts the specific data we focused on in our model development. The variables of interest are termed "Material Special Data" (MSD), and they code "types of occurrences which are encountered in mishap analysis." There are five such variables (first, second ... fifth MSD), and we chose to use the first, second and third due to large amounts of missing data in the fourth and fifth.

Each MSD variable has two types of codes. One type consists of three alpha characters (e.g., "AAA"; BBP"), which refers to broad comments about a mishap of a maintenance nature. For example, "AAA" means "Maintenance error - general" and "BBP" means "improper use of a safety or locking device (with photographs)." The other type consists of an alpha and two numeric characters (e.g., "L10"), referring to a specific subsystem. For example, "L10" means "landing gear over torque." The MSD variables, then, contain both the systems and maintenance information called for in our approach.

We pulled these data apart by writing a program to make a pass through the data and look for the alpha and alphanumeric codes. When it found an alpha code, the program placed it in a new, all-alpha variable and deleted it from the root variable. When it encountered an alphanumeric code, it left it alone and left blank that position in the all-alpha variable. The result was two variables, the root one containing only alphanumberic codes (system information) termed S1 and the second containing only alpha codes (maintenance information) termed M1. Then the process was repeated for the second and third MSD variables, resulting in S2, M2, S3 and M3.

The table at the bottom of Figure 2 shows how these six variables were cross-tabulated, with each systems variable crossed with each maintenance variable. Note that the S1 x M1, S2 x M2 and S3 x M3 tables make no sense,

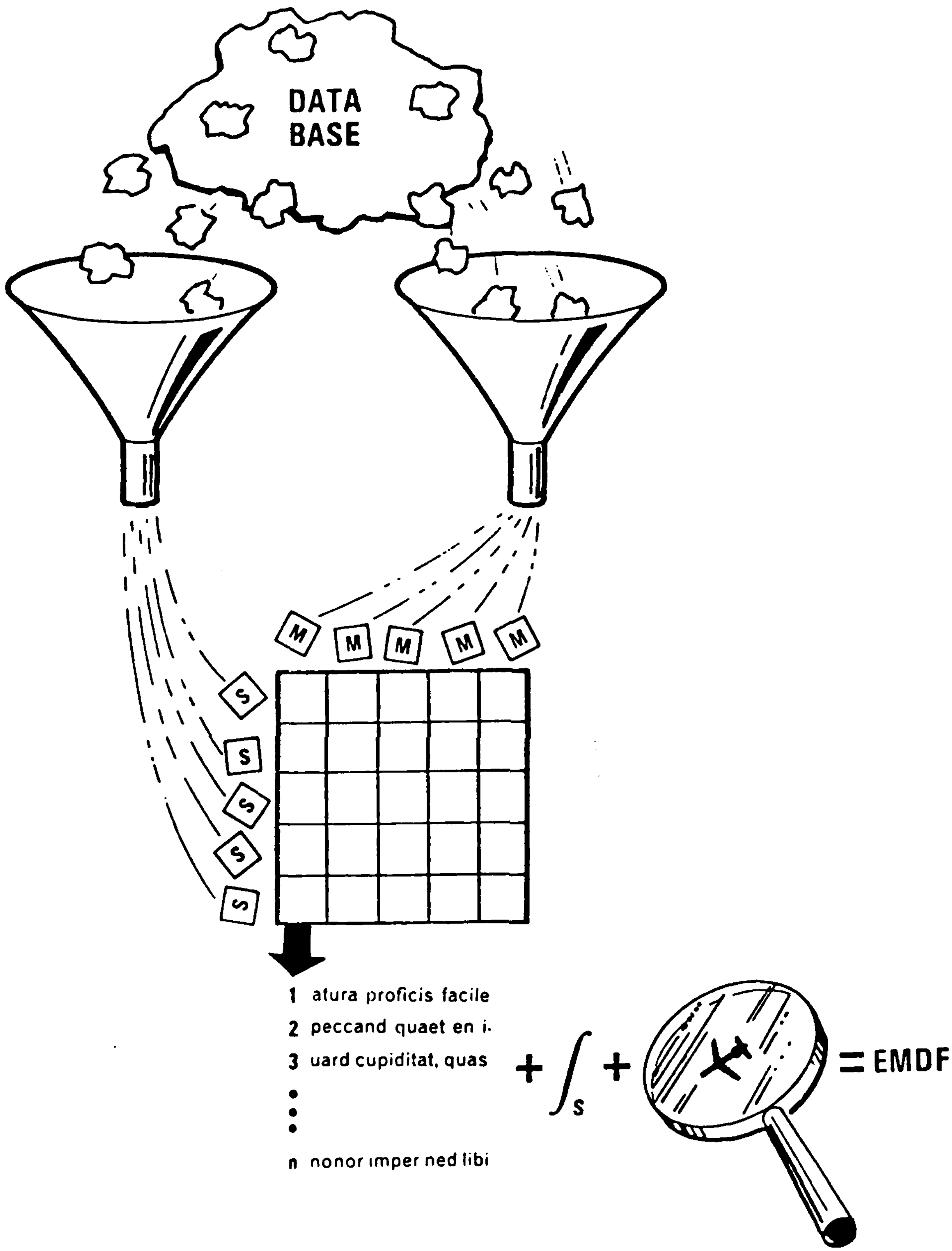


Figure 1. Model development process.

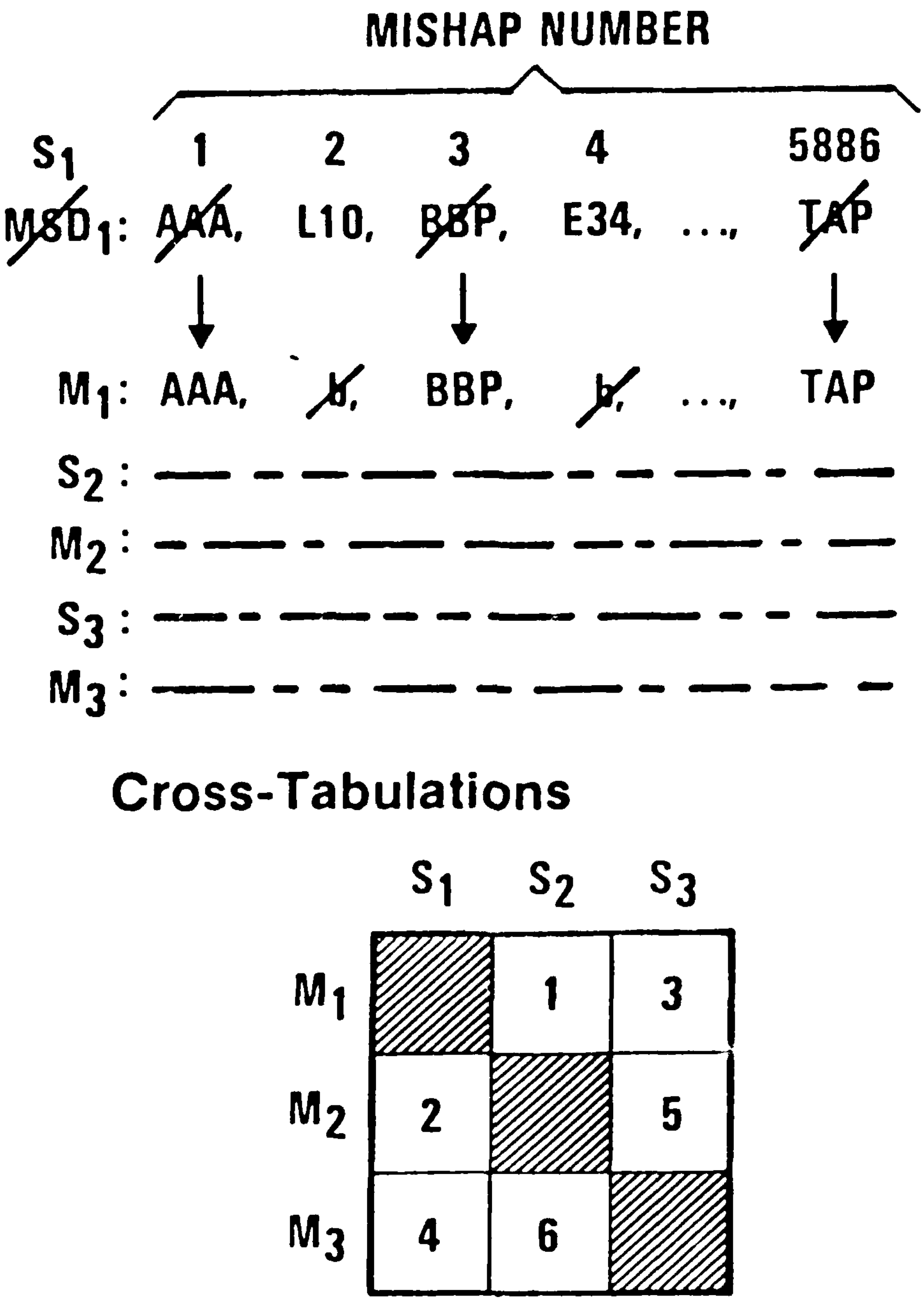


Figure 2. Material special data "massaging."

since each of these pairs is complementary within the pair or "zero correlated" in a nonparametric sense. That is, a case with an entry in S1 by definition has a blank in M1; if it has a code in M2 it must have a blank in S2, etc. The result is six useful tables, arbitrarily termed 1-6 in Figure 2.

In Table 5 we describe the results of our analysis of the cross-tabulation tables 1-6. We selected system codes which met a number of rather stringent criteria, including size (number of cases in the cell), at least 50 percent of such system codes co-occuring with the alpha, maintenance codes, small amounts (≤50 percent) of missing data and, in some cases, further component code data to narrow down the system being described. The effect of these criteria was to reduce the number of system codes by a factor of 12.5. Then we ranked the codes meeting all of these criteria according to the number of tables in which they did so; the systems eventually examined met the criteria in 3, 3, and 2 tables, respectively. Finally, when we selected three multitable codes which survived all of the criteria, we examined the distributions of those code combinations by aircraft, and listed the case record codes of those systems-by-maintenance combinations which co-occurred with the most frequent aircraft.

The case record codes were used to access the actual case narratives of the mishaps (which were delivered to us on hard copy for convenience of access). The three codes focused upon involved an ejection seat, external tanks, and an airspeed/altimeter pitot line. These narratives, and the EMDF inferences we drew from them, are summarized in Tables 6, 7 and 8.

Table 5

Results

- Three subsystem codes selected on basis of:
    - Number of cases
    - Maintenance personnel involvement codes
    - Sufficiently low level of missing data
    - Further component data
- Case narratives reviewed

I Ejection seat (inadvertent actuation)

- Pin security
- Resemblance to brake

II External tanks (inadvertent ground jettison)

- Pin security

III Airspeed/altimeter pitot line (instrument failure)

- Instrument panel access
- Drain plug

- 100% "hit rate" on applications of model thus far

Table 6 abstracts the case narratives relating to the escape seat situation uncovered. From them, two common themes emerge with potential bearing on EMDFs. The first is that even experienced, cockpit-qualified personnel, very familiar with the systems (e.g., "brakemen") sometimes mistake the seat firing handle for the emergency brake handle with extremely dangerous consequences. The second, a prerequisite for any of these mishaps, is that the safety pins are not always fully in position. When they are not (and they are almost always supposed to be when the aircraft is on the ground), a variety of handle-pulling, linkage-bumping, etc., errors can cause inadvertent actuation.

Dealing with the pin security issue first, it would appear that two areas for further study are obvious. The first is that sensors could be built into the pin holes such that when (a) the plane is on the ground and (b) the seat is not fully pinned, a cockpit alarm (visual, auditory or both) is set off, for the duration of the dangerous state (until the pins are replaced). The second possibility is to redesign pins so that they may be removed only by use of a special tool or key, and then restrict access to the key. Were only maintenance supervisors able to "arm" the seat, errors of lack of experience and/or training would greatly diminish or disappear.

As far as the firing handle's resemblance to the brake is concerned, this is a question requiring field inspection to evaluate. Whatever the resemblance in position, color, size, "feel," tension, etc., design modifications should be feasible to reduce these errors and mishaps.

Table 6

Case I

- D31/D02 (ejection seat)
- Ten cases
- All on ground
    - "No pin in; fatal; procedure violation"
    - "Asked unqualified person to pull brake"
    - "Pulled wrong handle during hydraulic checks"
    - "Night brake technician with no flash light"
    - "Oxygen bottle ignited; blew seat"
    - "Brake rider mistook handle"
    - "Personnel bumped actuator (not pinned)"
    - "Jacket snagged on cables/linkage"
    - "Using handle as handhold (not pinned)"
    - "Rider told to release brakes (not pinned)"

∴ • Cockpit status alarm (pin sensors)

- Locking pins (tool; key)
- Handle redesign

Table 7 contains abstracts of case narratives relative to inadvertent actuation of an auxiliary tank release system. All seven mishaps occurred on the ground during a regular morning inspection of the system. It appears that the test procedure for this aircraft calls for de-arming the tanks by checking the breeches and pulling the leads which go to the explosive charges. Then, the leads are connected to a test set, the system activated and the system operation and continuity check performed.

A common error seems to be for one or more of the charges to be de-armed but not the entire set of five. Both novice and experienced maintenance personnel are subject to this, although "experience," "training," "supervision," and "procedure violation" are usually cited. The consequence is usually for one side of a fuel tank to drop, pivoting the other end against the pylons, striking the floor with ensuing tank rupture and fuel spillage.

As with the escape seat activation example (Case I), the problem seems to have to do with safety pin security and, in general, status information about the equipment involved in, and thus the consequences of, the test. Status alarms could be built into the cockpit and provide "continue/stop" displays when an early event in the test sequence occurs. And, the test sets themselves could provide alarms when the test is about to occur when the aircraft is not fully de-armed. And finally, locking pins releasable only by tool or key held by maintenance supervisors would encourage that greater care and expertise be brought to bear on these tests.

Table 7

Case II

- G32 (bomb rack release system; droppable fuel tanks)
- Seven cases
- All on daily inspection
  - "Failed to insure rack pinned"
  - "Two of five not de-armed"
  - "One of five not de-armed"
  - "One of five not de-armed"
  - "Breeches not checked"
  - "Returned to wrong plane"
  - "Failed to de-arm"
- ∴ Central alarm to pin/de-arming mechanism (cockpit; test equipment)
- Locking pins (tool; key)

Our third case study is presented in Table 8. Here, sixteen narratives were found pertaining to a single code (False/Erratic Instrument Indication) and nine of these dealt specifically with the static pitot tube system. (A pitot tube is a device for transferring pressure changes and is used in the barometric altimeter system and the airspeed indicator.)

When we reviewed the nine pitot tube case narratives, we found that they fall neatly into two clusters, six dealing with crimped, pinched and loose lines where the tube mates with the altimeter, and three dealing with water in the pitot tube itself. Table 8 is organized according to these clusters.

The first cluster, crimped lines, is an example of what is termed "type d" maintenance error, that is, the damaging of equipment in the process of repair. The narratives indicate that the cramped design of equipment arrangement behind the panel may contribute to these errors. It appears that as instruments are replaced, and specifically as the pitot tube line is shoved back through the panel, the line is damaged.

Clearly, space is at a premium in a modern aircraft, but at some point an alternative design which minimizes the opportunity for pinching pitot lines should be considered. Specifically, one would think that a tubing guide or tensioned retracting mechanism could be utilized to guide the line past other rear-of-panel equipment. The second cluster, water in the pitot tube, is associated with the low point drain plug on the outside pitot line. Apparently, water collects and condenses inside the tube, and a routine maintenance action is to remove a plug, drain the water, and replace the plug cap; failure to replace the cap causes the mishaps. A direction to pursue toward an EMDF is for more fail-safe mechanisms, either a chain making the cap captive or some sort of spring-loaded plunger mechanism which, after being actuated to drain the water, would automatically move back into place.

Table 8

Case III

- 134 (false/erratic instrument indication)
- 9 of the 16 cases involved the pitot tube

A
- "Pitot line crimped at altimeter connection"
- "Pinched static line behind altimeter"
- "Loose pitot fittings"
- "Kink in altimeter/airspeed static line"
- "Incorrect mounting screws pierced pitot static probe"
- "Static hose twisted and crimped"

∴
- Pitot connections on back of airspeed indicator and altimeter
- Pitot connection change; retracting mechanism - tubing guide

B
- "Pitot drain cap removed"
- "Low point drain plug missing"
- "Water in pitot system"

∴
- Failsafe pitot drain mechanism

From this point of analysis, where do we proceed to validate these hypotheses and generate true EMDFs? Table 9 lists the steps we see at this time. First, we can attempt to find out more about these specific cases and all other cases of the same type (which may not have fallen out of our model readily). Then, we feel it is important to review (where possible) information gathered from the manufacturer and design team, to understand (a) why the design was implemented, (b) whether we fully understand the situation and (c) whether potential design changes are "don't cares" or if in fact, they might adversely affect other systems.

In field evaluation, we see both inspection (observation of maintenance; hands-on experience for human factors engineers) and interviews with maintainers to be useful activities. Finally, the scope and potentially a cost-benefit understanding of the problems and their solution can be derived from other data bases, especially 3-M which documents all Naval Air maintenance (not just maintenance causing mishaps). From all of these activities we hope that general design standards (EMDFs) will be able to be validly explicated.

Table 9

EMDF Derivation

- Review of detailed case records
- Manufacturer (design) review
- Field inspection
- Field interviews
- Validation with other data bases (3-M)
- Design standards

To conclude (Table 10), we feel that our Design for Effective Maintenance study has produced three reasonable examples of potential maintainability design flaws (EMDF hypotheses) drawn from existing data (AMD). Since the model was only applied three times, we have every reason to believe our approach would be successful in producing numerous (perhaps hundreds of) others. The methodology is not restricted to the Material Special Data approach taken herein, and other variable combinations within the AMD might be even more successful. And, there is no apparent reason why our approach could not be applied to other data bases, especially 3-M. We feel that this line of work, followed through in the manner described earlier, can have large and direct benefit to the overall Design-for-Maintainers program (and the human factors of maintainability in general) and we are currently working on specific proposals along those lines.

Table 10

Conclusions

• EMDF hypotheses generated for specific subsystems
• Methodology developed applicable to other subsystems in NSC/AMD
• Approach developed applicable to
• Other variable combinations within NSC/AMD
• Other data bases (e.g., 3-M)

Acknowledgement

Harris Government Electronic Systems Division is a hardware-oriented producer of a variety of systems for government customers, and is involved in direct technical support of these programs. John Schmitt is an Associate Principal Engineer (Human Factors/Safety). Larry Lamb is also an Associate Principal Engineer, and in addition has group leader responsibility for the Human Factors/Systems Safety group. John Mocharnuk is an Engineering Psychologist and the head of the Systems Effectiveness section, which includes Human Factors/Safety, Reliability/Maintainability, and EMI/EMC/TEMPEST.

Design, Implementation, and Evaluation of Approaches to Improving Maintenance Through Training

William B. Rouse

Center for Man-Machine Systems Research
Georgia Institute of Technology
Atlanta, Georgia

Maintenance is often discussed as a serious problem. In the military, poor maintenance is cited as a cause of low levels of operational readiness. In the private sector, maintenance problems have been noted as the cause of a shift away from American-produced goods. The sources of the maintenance problem include both increasingly complex equipment systems and decreasing skill levels of maintenance technicians.

Figure 1 depicts the relationships between three types of remedial measures and maintainer (or operator) performance. Selection involves using tests of ability, aptitude, and perhaps even cognitive style to identify potential trainees who are likely to excel, or at least be adequate, as maintenance technicians. Training involves providing the trainee with facts, principles, and experiences that will enable him to achieve maintenance performance objectives. Aiding denotes all aspects of the system design which are provided to enhance maintainer performance, including test points, modularity, test equipment, procedures, etc.

Figure 1 shows several loops feeding back from performance to selection, training, and aiding. Ideally, these three processes should be responsive to performance objectives. However, at least in the military, the responsiveness of selection is currently limited by the population available and the responsiveness of aiding is limited by the lengthy procurement process. Training, on the other hand, should be very responsive to performance feedback. This is due to the fact that the military, as well as much of industry, designs and conducts its own training programs and hence, should be able to adapt these programs to performance requirements. A mechanism by which this adaptation might be achieved is discussed in the following section.

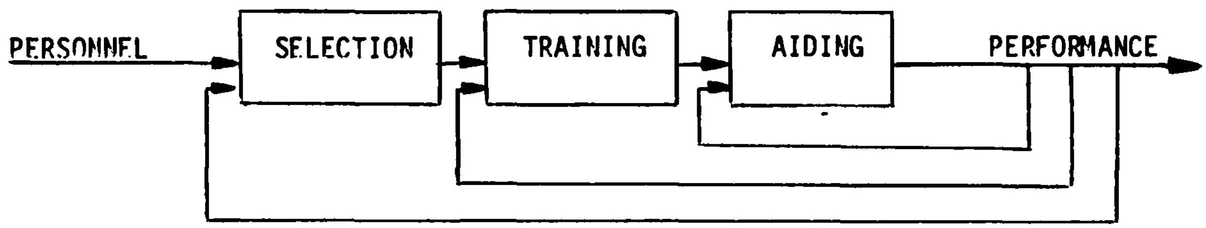


Figure 1. Relationship of selection, training, and aiding to performance.

Synthesis of Training Programs

Figure 2 shows the three phases of program synthesis and their relationship to trainee performance. Design includes choosing a maintenance philosophy regarding the role of the maintainer, choosing performance objectives and determining the skills necessary to achieve these objectives, and considering alternative training methods and technologies. Implementation involves sequencing and coordinating objectives with respect to a particular equipment system, integration of methods and technologies, and development of a performance measurement plan. Evaluation includes assessing trainee performance both during training and subsequently on the job, as well as estimating the impact of maintainer performance on system performance.

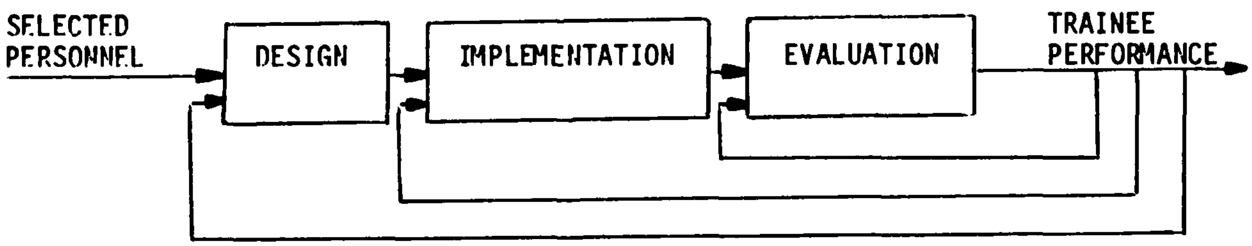


Figure 2. Synthesis of training programs.

Figures 1 and 2 represent two processes that are structurally similar. Both employ feedback to compare desired and actual performance, and both are assumed to have some mechanisms for adapting the process so as to produce actual performance that is close to the desired performance. Thus, the three essential features of the representations in Figures 1 and 2 are: 1) definition of desired performance, 2) feedback of actual performance, and 3) mechanisms for adapting the process. These three ingredients must be present if the approach to synthesizing training programs shown in Figure 2 is to be successful.

Unfortunately, this approach must be viewed as an idealization rather than reality. The basic difficulty is that desired maintainer performance, if it

is defined at all, is defined in terms of global measures such as MTTR (mean-time-to-repair), NEOF (no evidence of failure) rate, and RTOK (retest ok) rate. These measures are not sufficiently diagnostic to provide for an adaptive mechanism, a reasonably clear path of adaptation. A further difficulty is that performance feedback is often nonexistent or is so highly aggregated that it can, at best, only serve as a warning device that a class of equipment systems is experiencing maintenance problems.

While one might argue that the success of the approach to program synthesis depicted in Figure 2 is also limited by a lack of a knowledge base upon which the design of adaptive mechanisms can be founded, this is really a secondary difficulty. Until desired maintainer performance is defined at an appropriate level and, until performance feedback of suitable measures is instituted, the knowledge base cannot be expanded and certainly not exploited. The central problem is defining and measuring performance.

Maintainer Performance

Discussions of performance usually focus on the overall objective of system performance expressed in terms of both capabilities and availability or operational readiness. These global measures are affected by five constituent subsystems: hardware, software, support, operators, and maintainers. Thus, the maintainer makes only one of many contributions to system performance, and overall measures of system performance do not necessarily provide clear insights into the maintainer's contribution.

As noted earlier, overall maintenance-oriented performance measures such as MTTR, NEOF, and RTOK also do not provide great insights into maintainer performance. What is necessary is an understanding of the process which the maintainer goes through in achieving some particular level of overall maintenance performance. There appear to be two rather different ways of gaining this understanding: task analysis and modeling.

For frequent or well-defined abnormal and emergency situations, the required sequence of human observations, decisions, and actions can be determined via task analysis. Specific behavioral objectives can then be chosen and appropriate procedures designed. There are many excellent examples of where this task analysis approach to defining maintainer (or operator) performance has succeeded admirably.

However, while task analysis may be viewed as necessary, it is not sufficient. For infrequent or ill-defined situations, or for multi-event situations, the required sequence of observations, decisions, and actions may be very difficult to determine. Indeed, it may even be very difficult to define the nature of such situations.

This aspect of the maintainer's role is best viewed as problem solving (Rouse, 1981, 1982). A reasonable approach to understanding the maintainer as a problem solver is through the use of models that attempt to capture the essence of the problem solving skills required for maintenance tasks. Such models can be used as a basis for devising and evaluating the dimensions of problem solving performance relevant to maintenance tasks. These dimensions can provide insight into the problem solving principles (as opposed to procedures) that maintenance technicians need to know in order to succeed in infrequent, ill-defined, or multi-event situations.

A recent study of a wide variety of measures of problem solving performance in maintenance tasks (Henneman & Rouse, 1982) concluded that there are three basic dimensions of performance: time, error, and inefficiency. Time refers to the cumulative "active" time required for a maintenance operation. Errors are defined as observations, decisions, or actions that result in no progress relative to the goal of the maintenance operation. Inefficiencies are observations, decisions or actions that yield progress, but not as much progress as is possible. (For further discussion of similar definitions, see also Duncan & Gray [1975] and Hunt & Rouse [1981].)

Measures of performance on the dimensions of time, errors, and inefficiency should provide the insights necessary to isolate the sources of problems detected in terms of high MTTR, NEOF, or RTOK. Time is relatively straightforward to measure, although "active" time can be difficult to identify. Identifying, and particularly classifying, errors can be a rather intensive process, but provides multifaceted insights. Inefficiency often is difficult to measure because it requires that one determine the characteristics of efficient problem solutions for infrequent, ill-defined, and/or multi-event situations. Overall, considering the trade-off between ease of measurement and richness of information, human error is probably the most interesting dimension of maintainer performance.

Human Error

Human error is a topic of great interest to many people ranging from pyschoanalysts to psychologists to reliability engineers. A wide variety of theories and classification schemes have been proposed and, in a few cases, evaluated. Recently, a comprehensive methodology for analysis and classification of human errors has been proposed and applied to studies of human error in three fairly different domains (Rouse & Rouse, 1982).

For the purposes of this paper, the main interest in human error is as a performance measure suitable for closing the loops shown in Figure 2. Further, error has a particularly attractive feature in that its desired level can be set a priori as zero. (In this respect, time and inefficiency are not so straightforward; zero time and inefficiency may be desirable, but not realistically achievable.) Thus, human error inherently provides a definition of desired maintainer performance as well as a means of feeding back actual maintainer performance. The next question is whether or not this results in the process depicted in Figure 2 being able to adapt.

Such adaptation is possible. However, it requires that human error be analyzed and classified at a fairly fine-grained level. Rouse and Rouse (1982) have proposed a classification scheme involving 6 general and 31 specific categories of human error. The general categories include human error related to:

1. Observation of system state
2. Choice of hypothesis
3. Testing of hypothesis
4. Choice of goal
5. Choice of procedure
6. Extension of procedure.

(The specific categories are too numerous to list and define within this

paper.) The sources of data used to identify and classify human error include observer notes, questionnaires, and interviews as well as recordings of system state variables, communications among personnel, and occasionally verbal protocols (i.e., "thinking aloud").

The methodology has been applied within three studies. Within a study of aircraft mechanics, the methodology was used to identify a training deficiency and subsequently evaluate an improved training program (Johnson & Rouse, 1982). For a study of aircraft pilots, the methodology was employed to identify the benefits of a computer-based display system in terms of a substantial decrease in the frequencies of certain types of error (Rouse, Rouse, & Hammer, 1982; Rouse & Rouse, 1982). Within a study of supertanker engineering officers, the methodology was utilized to identify deficiencies in the design of the control panel and inadequacies in the operator's knowledge of system functions which led to a plan to modify the training program (van Eekhout & Rouse, 1981). Taken as a whole, these three studies show that defining performance appropriately can lead to the type of adaptations represented in Figures 1 and 2.

Conclusions

This paper has proposed that training is one of the most responsive means available for adapting to meet performance objectives. It was suggested that suitable definitions of desired performance and measures of actual performance are needed in order for the potential adaptivity of training to be realized. The use of human error to provide the necessary measures of desired and actual performance was discussed and results of utilizing these measures briefly reviewed.

The implications of the point of view espoused in this paper go beyond analysis and classification of human error. The broadest and most important implication is that feedback is necessary if maintenance (or operational) problems are to be lessened or eliminated. While the feedback provided by existing maintenance record systems (i.e., 3-M, TAMMS, and 66-1/66-5) may be sufficient as a warning device for noting the presence of problems, it is insufficient for isolating the sources of problems. Once problems are detected, a more fine-grained analysis is necessary. Thus, one can envision there being at least two levels of feedback; one for detecting problems and one for isolating causes and adapting appropriately.

References

Duncan, K. D., & Gray, M. J. An evaluation of a fault-finding training course for refinery process operators. Journal of Occupational Psychology, 1975, 48, 199.

Henneman, R. L. & Rouse, W. B. Measures of human performance in fault diagnosis tasks. Manuscript submitted for publication, 1982.

Hunt, R. M. & Rouse, W. B. Problem solving skills of maintenance trainees in diagnosing faults in simulated powerplants. Human Factors, 1981, 23, 317.

Johnson, W. B. & Rouse, W. B. Analysis and classification of human errors in troubleshooting live aircraft powerplants. IEEE Transactions on Systems, Man, and Cybernetics, 1982, 12.

Rouse, S. H., Rouse, W. B., & Hammer, J. M. Design and evaluation of an onboard computer-based information system for aircraft. IEEE Transactions on Systems, Man and Cybernetics, 1982, 12.

Rouse, W. B. Experimental studies and mathematical models of human problem solving performance in fault diagnosis tasks. In J. Rasmussen & W. B. Rouse (Eds.), Human Detection and diagnosis of system failures. New York: Plenum Press, 1981.

Rouse, W. B. Models of human problem solving: Detection, diagnosis, and compensation for system failures. Proceedings of IFAC Conference on Analysis, Design, and Evaluation of Man-Machine Systems, Baden-Baden, West Germany 1982.

Rouse, W. B. & Rouse, S. H. Analysis and classification of human error. Manuscript submitted for publication, 1982.

van Eekhout, J. M. & Rouse, W. B. Human errors in detection, diagnosis, and compensation for failures in the engine control room of a supertanker. IEEE Transactions on Systems, Man, and Cybernetics, 1981, 11, 813.

Cost-Effectiveness of Maintenance Simulators for Military Training

Jesse Orlansky
Joseph String

Institute for Defense Analyses
Alexandria, Virginia

This paper compares the cost-effectiveness of maintenance training simulators and actual equipment trainers for use in training military personnel how to maintain operational equipment. Both types of equipment have been used for training personnel to perform corrective and preventive maintenance at organizational and intermediate levels.

An actual equipment trainer is simply a unit of operational equipment brought into a school for training purposes. It may or may not be modified to make it operate in a classroom and to be more convenient for training purposes. A *maintenance training simulator* is a device that, in some way, mimics operational equipment for use in training. In recent years, there has been a trend to use maintenance training simulators rather than actual equipment for training purposes. Maintenance simulators are said to have advantages over actual equipment for use in training such as lower cost, ability to demonstrate a wider variety of malfunctions and more freedom from breakdown in the classroom.

Characteristics of Maintenance Simulators

Maintenance simulators differ in how closely they resemble actual equipment, in their functional capabilities as instructional devices, and in their complexity and cost. These simulators are often characterized as 2-D or 3-D devices, i.e., as being two- or three-dimensional in their physical form; some simulators contain both 2-D and 3-D components.

The manufacturers of 2-D simulators have developed software packages, computer and support components that can be used in a number of different simulations. This has led us to distinguish between, what we call later in discussing costs, "standard" and "nonstandard" maintenance simulator systems. Standard systems, whether they are 2-D or 3-D simulators, are likely to cost less than nonstandard systems. A 3-D simulator permits "hands on" practice in manual maintenance skills not possible on many 2-D simulators; it also has greater physical similarity to the actual equipment. Whether or not greater

physical similarity increases the effectiveness of training is a proper question.

Advantages of Maintenance Simulators

The major advantage of a maintenance simulator is that it is designed to be used as a training device and to provide facilities important for instructing students. In contrast, actual equipment is designed to operate effectively under a variety of stressful conditions in the field; it is not meant to be used as a training device.

Maintenance simulators can be designed to include a large variety of malfunctions with which maintenance personnel should be familiar, including faults that cannot be demonstrated conveniently on actual equipment trainers or that occur rarely in real life. All modern maintenance simulators incorporate some type of computer support. Thus, the symptoms of many types of complex faults can be stored in the computer and selected simply by a control setting on the instructor's console. Computer-supported equipment can also record what the student does, thereby reducing the need for constant observation by the instructor. The instructor can use information collected by the computer to guide each student; a computer can also assist the student without an instructor's intervention. Records of student performance and achievement can be maintained automatically. Simulators can be made rugged enough to sustain damage or abuse encountered from students. Thus, they can provide greater reliability and availability in the classroom than is often found with actual equipment. Training which would be avoided because of safety reasons, e.g., exposure of students to dangerous electrical currents or hydraulic pressures, can be undertaken with little risk with a simulator. If students using such equipment complete their training in less time, as has often been found with computer-based methods of instruction, there are potential cost reductions due to savings in student time, increased throughput of students and reduced need for instructors and support personnel.

A simulator need not contain all the components found in the actual equipment. Thus, it is often possible to build a simulator that has greater flexibility and capacity for training and that costs less than an actual equipment trainer.

Disadvantages of Maintenance Simulators

There are some disadvantages to the use of simulators. The procurement of maintenance simulators necessarily involves some costs to design and build this special equipment, to develop course materials, maintenance procedures, support and documentation. The types of training provided by simulators may not provide the student with all the skills needed to maintain operational equipment, an outcome that seems assured when actual equipment is used for training. A new simulator may not be ready when needed for training because its design and development necessarily follows that of the actual equipment; modifications in the design of the actual equipment may delay completion of the simulator, which must be modified accordingly. If there are many and frequent modifications, the original simulator may have to be redesigned totally, sometimes at a large cost, in order to be useful for training.

Data on the effectiveness and cost of maintenance simulators and actual equipment trainers are considered next.

The Effectiveness of Maintenance Simulators

The purpose of maintenance training, whether with simulators or actual equipment trainers, is to qualify technicians to maintain equipment in the field. In fact, however, the effectiveness of maintenance simulators for training technicians has been compared to that of actual equipment trainers only on the basis of student performance at school and not on the job; an exception to this general statement (Cicchinelli, Harmon, Keller & Kottenstette, 1980) will be discussed later. The lack of job performance data to validate training applies generally to all types of military training and not to maintenance training alone.

Effectiveness of Maintenance Simulators at Schools

We found 12 studies, conducted over the period of 1967 to 1980, that compare the effectiveness of maintenance simulators and actual equipment trainers in a variety of courses at military training schools; these are summarized in Table 1. Most of the maintenance simulators apply to electronics and aviation; one, the Hagen Automatic Boiler Control, involves an electro-mechanical control system for ships.

Student Achievement

Effectiveness was evaluated by comparing the scores, in end-of-course tests, of students who used simulators with those who used actual equipment trainers. There are 13 comparisons; in 12 of these, students trained with simulators achieved test scores the same as or better than those trained with actual equipment; in one case, scores were lower. The differences, though statistically significant, have little practical significance.

Cicchinelli et al. (1980) compared supervisors' ratings on the job performance of technicians trained either with a maintenance simulator (the 6883 Test Station 3-D Simulator) or an actual equipment trainer. Field surveys provided ratings on the job performance of course graduates (some twice); some were on the job as long as 32 weeks. The supervisors did not know how the students had been trained. Their ratings showed no noticeable difference between the performance of technicians trained with the simulator or with the actual equipment trainer. The abilities of the technicians in both groups increased with amount of time on the job.

Time Savings

The automated and individualized method of instruction that is an inherent characteristic of modern maintenance simulators should be expected to save some of the time students need to complete the same course when given by conventional instruction (Orlansky & String, 1979). Time savings are reported in three of the studies shown in Table 1. Compared to the use of actual equipment trainers, maintenance simulators saved 22, 50 and 50 percent, respectively, of the time students needed to complete these courses. Although no explanations are offered for these time savings, one could surmise that

Table 1

Summary of Studies on the Effectiveness of Maintenance Simulators, 1967-1980*

SIMULATOR	COURSE	COURSE LENGTH (STANDARD)	COMPARISONS: SIMULATOR TO ACTUAL EQUIPMENT							REFERENCE
			NO. OF SUBJECTS(3)	EFFECTIVENESS(1)				ATTITUDE TO SIMULATORS(2)		
				POORER	SAME	BETTER	TIME SAVINGS	STUDENTS	INSTR.	
Generalized Sonar Maintenance Trainer	Sonar maintenance (special course)	4 days(3)	9		•		22%(4)	Students favorable		Parker and DePauli, 1967
	Intermediate General Electronics	4 weeks	20		•					DePauli and Parker, 1969
EC II	APQ-126 Radar		17					+		Spangenburg, 1974
	Mohawk Propeller System	3 hrs	33			•				Darst, 1974
	Hydraulic and Flight Control	32 hrs	13		•	•		+	–	Wright and Campbell, 1975
	Engine, Power Plants and Fuel	24 hrs	13	•	•			+	–	Wright and Campbell, 1975
	Environmental/Utility System	32 hrs	9		••			+	–	Wright and Campbell, 1975
	APQ-126 Radar	60 hrs	15		••			0/+	0/+	McGuirk, Pieper, and Miller, 1975
										Platt, 1976
								+	+	Biersner, 1975
	Pilot Familiarization, T-2C	18 hrs	6						+	Biersner, 1976
	Flight Officer Familiarization, TA-4C	11 hrs	30						+	Biersner, 1976
Automated Electronics Maintenance Trainer	FM Tuner									Modrick, Kanarick, Daniel, and Gardner, 1975
	Power Control for ALM-64 Test Equip									Modrick, Kanarick, Daniel, and Gardner, 1975
	ALM-106B Test Set									Modrick, Kanarick, Daniel, and Gardner, 1975
	Visual Target-Acquisition System									Modrick, Kanarick, Daniel, and Gardner, 1975
Generalized Maintenance Training System	SRC-20 UHF Voice Command System		20				ABOUT 50%	+		Rigney, Towne, King, and Moran, 1978
	SPA-61 Radar Repeater	16 hrs	10					+		Rigney, Towne, Moran, et al., 1978
Fault Identification Simulator	Hagen Automatic Boiler	5 wks	16		•		ABOUT 50%			Swezey (In Kinkade 1979)
6883 Converter/ Flight Control Systems Test Station	F-111 Avionics Maintenance	6 days(5)	56		•			+	0/+	Cicchinelli, Harmon, Keller and Kottenstette, 1980

(1)Some studies provide more than one comparison.

(2) + favorable, 0 neutral, – negative; 0/+ neutral to mildly favorable

(3)Simulator only.

(4)Average of five maintenance tasks in final test.

(5)Training with 6883 takes 2 days in a 23-week course; 6 days in this special test.

*Orlansky and String, 1981

they are due to factors such as that brighter students can complete a self-paced course faster than one given by conventional, group-paced instruction, that maintenance simulators generally have greater availability in the classroom than do actual equipment trainers and that instructors need less time to set up training problems and/or to insert malfunctions in simulators than in actual equipment trainers.

Attitudes

Based on questionnaires administered at the completion of the courses, students favor the use of simulators in 9 out of 10 cases and are neutral in one. Instructors are divided evenly as being favorable, neutral or unfavorable to the use of simulators (about one-third each).

Conclusions

Overall, maintenance simulators appear to be as effective as actual equipment trainers for training military personnel at schools; there is only one contrary finding. The effect of training upon job performance is reported only by Cicchinelli et al. (1980), who found no difference between those trained with a simulator and those with an actual equipment trainer.

The Cost of Maintenance Simulators

In order to deal with the issue of costs, we divided simulators into three classes.

Standard Systems

This class of maintenance simulators is based on standardization of the physical configuration. Such simulators consist of two elements: one element, called here the "general simulation system" constitutes a generalized and adaptable (but incomplete) simulation capability that can satisfy a wide range of specific training applications. The second element tailors the general simulation system to a particular training application; it is typically limited to courseware and pictorial or other representations (i.e., the simulation model) of the particular equipment being simulated. Standard systems were the earliest type to be used for maintenance training and are the only class to achieve extensive use. Compared with the other classes of simulators, the standard systems are generally low in cost and limited in terms of the complexity of processes that can be simulated. About 650 units of standard simulators have been procured for about 200 different training applications (many produced by ECC, Burtek, Ridgeway, and Lockheed).

Nonstandard Systems

The outstanding characteristic of nonstandard systems is diversity with respect to contractors and types of contracts, program purpose, numbers of devices manufactured, physical characteristics, complexity, and cost. The physical characteristics of the nonstandard simulators vary widely and include two- and three-dimensional trainers. There is wide variability in the software. Further, since most nonstandard systems typically simulate only one operational system, there is no definitive separation between software and

courseware functions. At the time of writing, there were 17 nonstandard maintenance simulator programs that should produce 47 unique simulations (e.g., the Mk 92 Fire Control System, Close-In Weapon System, F-16, MA-3, and 6883 Test Bench) and the delivery of 687 units, i.e., individual trainers. Producers of these simulators include Honeywell, Vought, Appli-Mation, Grumman, and RCA.

CAI-Like Systems

A CAI-like maintenance simulator is a computer-assisted instruction (CAI) system with courseware designed specifically to train maintenance skills. A typical CAI system uses two-dimensional displays (cathode ray tube and/or random access slides, microfiche, or videodisc to present lesson materials, pictures of equipment and the like) under control of a computer that also monitors student progress, prescribes lessons, and scores tests. When adapted to maintenance training, the CAI features are retained, and the trainer may also employ three-dimensional versions of equipment. Examples of such systems are the Navy Electronic Equipment Maintenance Trainer and the Army Maintenance Training and Evaluation Simulation System. Insufficient cost data were available on CAI-like maintenance simulators and they are not discussed further.

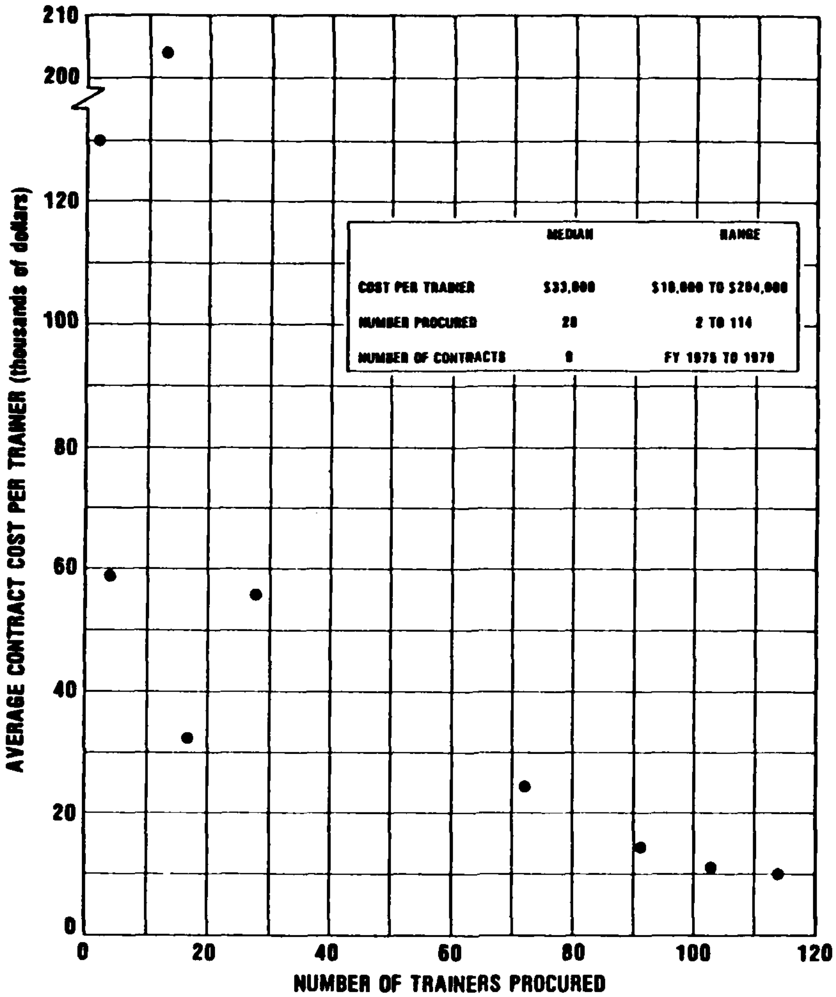
Costs of Maintenance Training Simulators

We found that the data now available on standard systems are insufficient to analyze their elements of cost and to relate these cost elements to the physical and performance characteristics of the trainers. In effect, it is now difficult or impossible to identify the major cost distinctions (e.g., between recurring and nonrecurring costs, between development and fabrication, between hardware and software) that allow characteristics of the simulator to be related to the total cost of the simulator program.

Data from nine contracts for standard simulators were reviewed, and the information they contain is shown in Figure 1. These contracts involve the development of 67 different models of simulators and the delivery of a total of 444 units. The figure shows average contract cost per delivery (total contract value divided by the number of trainers procured) vs. the number of trainers procured in each contract. These simulators ranged in unit cost from about $10 thousand to $204 thousand each with a median cost of about $33 thousand. The unit cost is reduced as the number of units in each contract increases. However, caution is advised in using the data in this figure. The individual contracts involve varying numbers of simulation models as well as quantities of trainers; both the simulation models and the trainers vary in complexity, physical, and performance characteristics.

The cost of 13 nonstandard maintenance simulators is shown in Table 2. The estimates are normalized to show recurring production costs adjusted to reflect a production quantity of one. These simulators range in cost from $100 thousand to $4.5 million; the median value is $900 thousand.

Nonrecurring costs account for a large portion of the total program costs of nonstandard maintenance simulators--over 70 percent when only one unit is fabricated and about 50 percent when five or six are fabricated (Figure 2). Software and courseware account for 10 to 45 percent of total program costs (Figure 3).



9-10-81-38

Figure 1. "Standard" maintenance simulators: average cost per per trainer vs. number of trainers procured.

Table 2

Nonstandard Maintenance Simulators: Cost of 13 Trainers (Normalized to Production of One Unit)

TRAINER	COST $ (000)
AN/TPS-43 GROUND RADAR	$ 100
TRIDENT AIR CONDITIONER	135
TRIDENT HIGH PRESSURE AIR COMPRESSOR	140
F-111D AVIONICS TEST BENCH (2-D 6883)	395
A-6E TRAM	475
MA-3 GENERATOR/CONSTANT SPEED DRIVE TEST STAND	525
AWACS RADAR SYSTEM	900
F-111D AVIONICS TEST BENCH (3-D 6883)	920
A-7E HEADS-UP DISPLAY TEST BENCH	1295
F-4J/N (AT TRAINER)	1540
AWACS NAVIGATION/GUIDANCE SYSTEM	2460
TRIDENT INTEGRATED RADIO ROOM - MAINTENANCE TRAINER	2625
TRIDENT INTEGRATED RADIO ROOM - OPERATOR/ MAINTENANCE TRAINER	4465

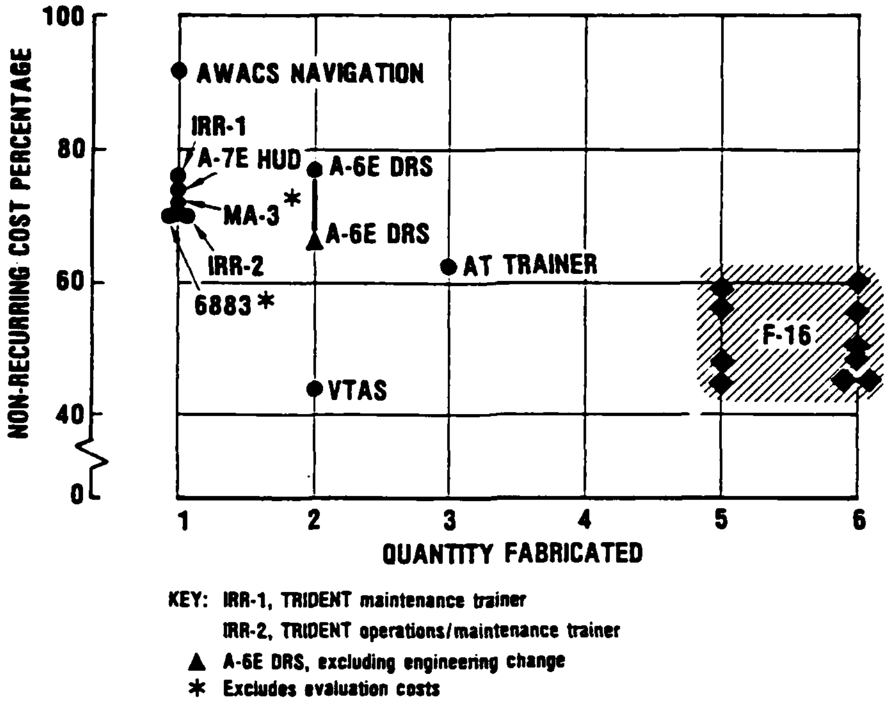


Figure 2. Nonstandard maintenance simulators: nonrecurring cost as a percent of program cost, according to quantity fabricated.

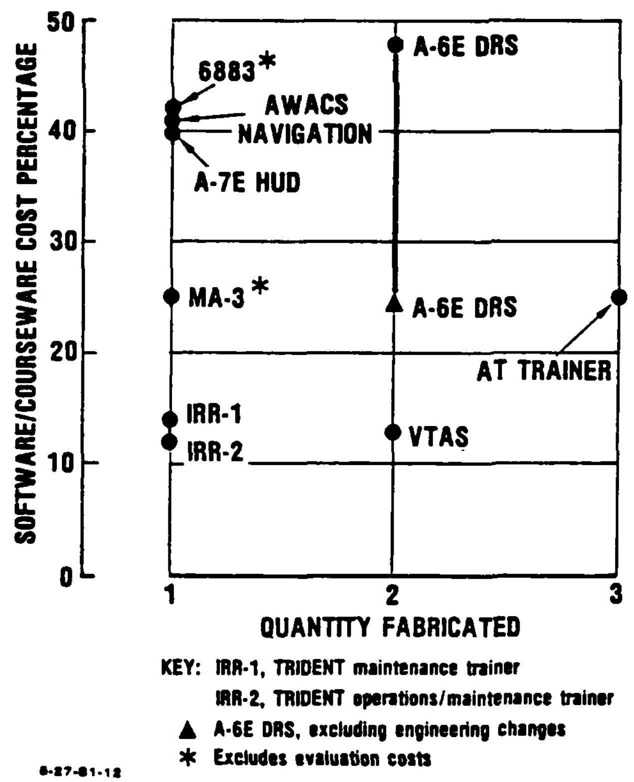


Figure 3. Nonstandard maintenance simulators: software and courseware cost as a percent of program total cost, according to quantity fabricated.

Cost-Effectiveness of Maintenance Simulators

Student achievement at school, as reported above, is about the same whether students are trained with maintenance simulators or with actual equipment trainers. Therefore, the cost-effectiveness of maintenance simulators depends on how much they cost, compared to the cost of actual equipment trainers. There is one comparison of life-cycle costs that we will consider separately. The cost comparisons that follow are incomplete because they include only acquisition costs.

The cost of an actual equipment trainer is the recurring production cost of an additional unit of equipment, under procurement as part of some weapon system, and does not include any costs of research, development, test and evaluation (RDT&E). Adapting a production unit for use in training, such as by adding power, special inputs and controls, may require some additional costs.

We were able to get relatively complete data, useful for comparative purposes, on both maintenance simulators and actual equipment trainers, for 11 cases; actual equipment trainers had not been used previously in some cases where maintenance simulators were developed recently for training. Some of the simulators are prototypes, rather than production units. Data on these simulators include the costs of RDT&E. These should be removed in order to make a fair comparison with the cost of actual equipment trainers which, as noted above, exclude the costs of RDT&E. The number of maintenance simulators procured could also influence the cost of a single unit; this varied from 1 to 36.

We decided to use values which would provide high and low estimates for the cost of one maintenance simulator. These were:

<u>High cost estimates</u>. Total program costs adjusted to reflect a production quantity of one; this includes the nonrecurring costs of research and development but not of test and evaluation and the recurring production cost of one unit. We call this the "Simulator Normalized Total Program Cost."
<u>Low cost estimate</u>. The recurring fabrication cost of one follow-on maintenance simulator. We call this the "Simulator Unit Recurring Fabrication Cost."

The high cost estimates are shown in Figure 4. The ratio of simulator/actual equipment trainer costs is 0.60 or less for seven cases (range 0.25 to 0.55). There are four cases where this ratio varies from 1.60 to 4.00 (VTAS, MA-3, AT Trainer and AWACS). We believe these data are suspect for the following reasons: in two cases, the operational equipments are relatively old and their costs have not been adjusted to reflect replacement values; in two cases, the simulator programs incurred costs for tasks beyond simply developing a simulator for routine training. For these reasons, we decided to accept 0.60 as an upper limit for the relative cost of a maintenance simulator compared to an actual equipment trainer.

The low cost estimates, based on the recurring cost of these simulators, are shown in Figure 5. Nine of the 11 cases fall at 0.20 or lower; the range

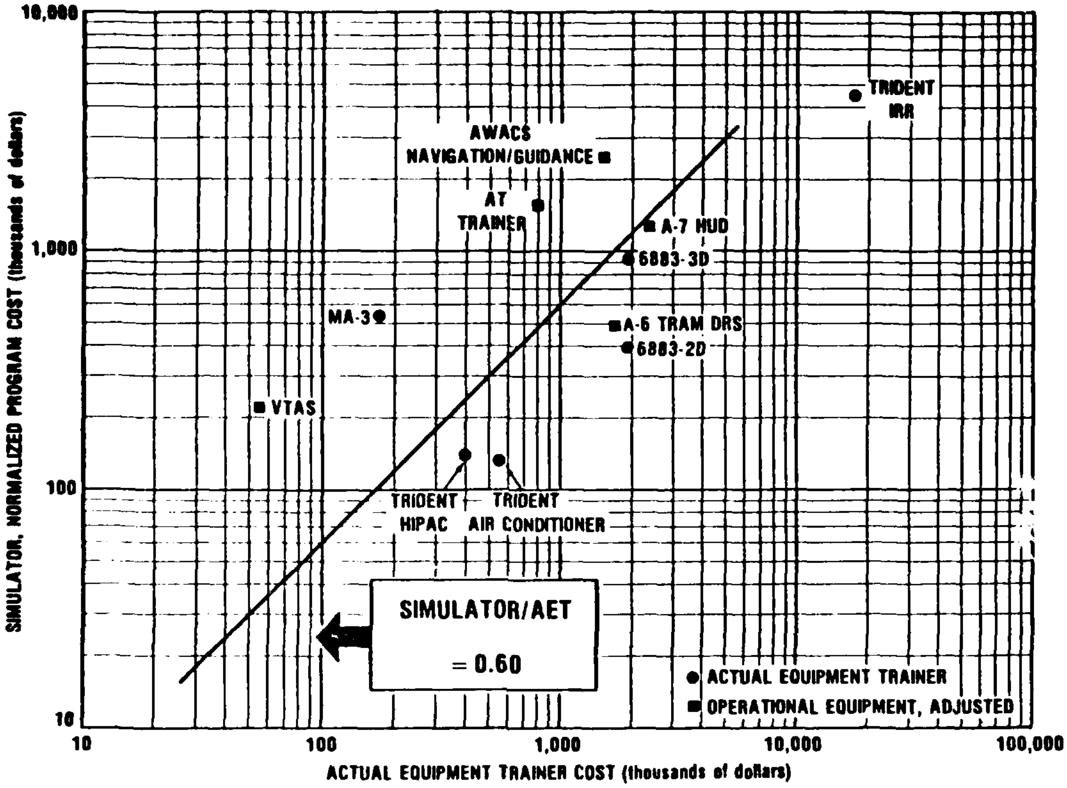


Figure 4. Relation between costs of actual equipment trainer and of simulator normalized program.

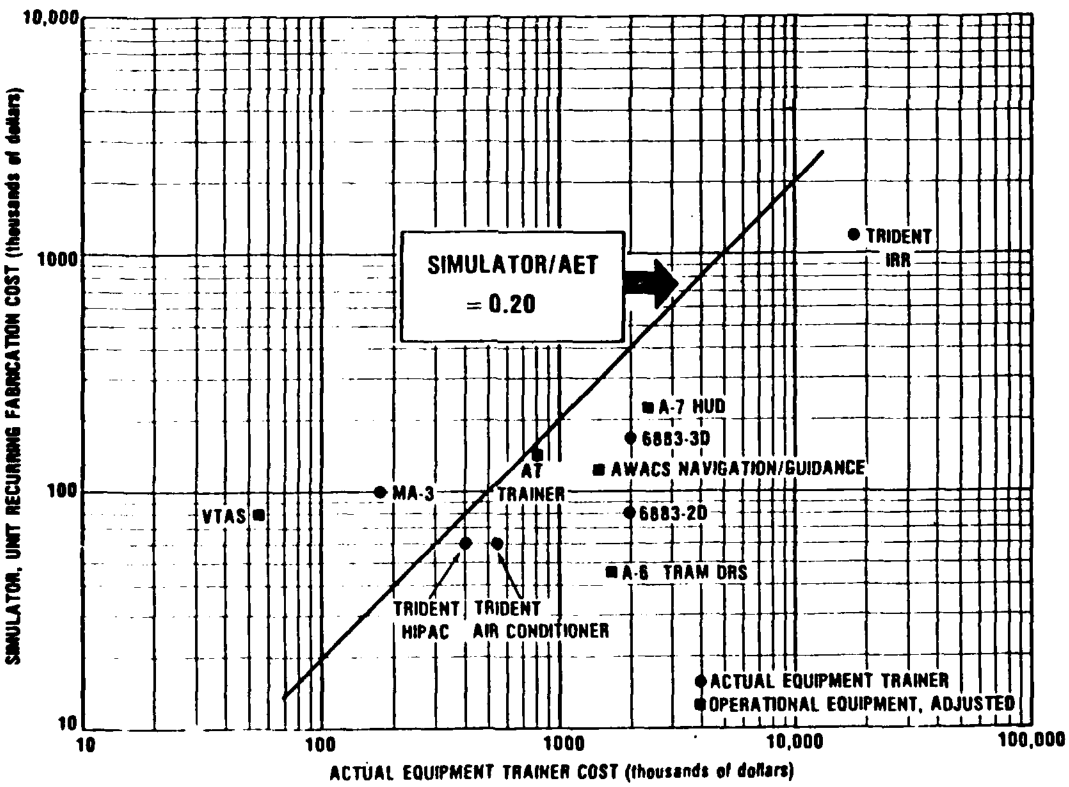


Figure 5. Relation between costs of actual equipment trainer and of simulator unit recurring fabrication.

is 0.03 to 0.19. The two outliers (VTAS and MA-3) are regarded as atypical for the reasons set forth above.

The cost-effectiveness of a maintenance simulator on a life-cycle basis has been evaluated only in one case that compares the Air Force 6883 Test Stand 3-Dimensional Simulator with the 6883 Actual Equipment Trainer (Cicchinelli et al., 1980). The three-dimensional simulator and actual equipment trainer were equally effective when measured by student achievement at school; supervisors' ratings showed no difference between the job performance of students trained either way for periods up to 32 weeks of experience after leaving school.

The life-cycle cost comparison of simulator and actual equipment trainer is shown in Table 3. Costs were estimated in constant 1978 dollars over a 15-year period and discounted at 10 percent. The results show that the total cost per student-hour was $23 for the simulator and $60 for the actual equipment trainer, i.e., 38 percent as much for the simulator, compared to the actual equipment trainer, for all costs over a 15-year period. The simulator costs less to procure ($595 thousand vs. $2105 thousand, or 28 percent as much) and less to operate ($1588 thousand vs. $3367 thousand or 47 percent as much) over a 15-year period.

We draw the following conclusions:

Cost. Maintenance simulators cost less to procure than do actual equipment trainers, i.e., 20 to 60 percent as much, using the low and high cost estimates, and less on a life-cycle basis.
Effectiveness. Achievement at school is the same when students are trained with maintenance simulators or with actual equipment trainers. This finding applies to 12 out of 13 cases in which such comparisons were made.

Table 3

6883 Test Stand: 15-Year Life-Cycle Costs of Actual Equipment Trainer and 3-Dimensional Simulator*

ITEM	(THOUSANDS OF DOLLARS) ACTUAL EQUIPMENT	3-D SIMULATOR	SIMULATOR/ AET(%)
ACQUISITION	$2105	$ 595	28%
RECURRING COSTS	3367	1588	47
TOTAL	5472	2183	40
NET PRESENT VALUE (1978 DOLLARS)	3896	1501	39
COST PER STUDENT HOUR	60	23	38

*Chicchinelli, Harmon, Keller, Kottenstette, 1980

Discussion

Maintenance simulators are cost-effective compared to actual equipment trainers.

This finding is necessarily qualified by the limited nature of the data from which it is derived. Effectiveness, as used here, is based on performance demonstrated at school rather than on the job. Cost, in all but one case, refers to the initial costs of acquiring training equipment and does not include the costs associated with the long-term use of simulators or of actual equipment for training, e.g., maintenance and upkeep, instructors and support personnel, student pay and support. In the one case where a life-cycle cost comparison was made, total cost per student-hour over a 15-year period for the 6883 Test Stand 3-Dimensional Simulator was 38 percent as much as for the actual equipment trainer. Both were equally effective as measured by tests at school and by supervisors' ratings of performance on the job after leaving school.

Conclusions

1. Maintenance simulators are as effective as actual equipment trainers for training military personnel, as measured by student achievement at school and, in one case, on the job. The use of maintenance simulators saves some of the time needed by students to complete courses, but data on this point are limited. Students favor the use of maintenance simulators; instructors are favorable, neutral, or negative to the use of simulators in about equal amounts.

2. The acquisition cost of maintenance simulators is typically 20 or 60 percent that of actual equipment trainers, depending upon whether simulator program nonrecurring costs are included or not. One life-cycle cost estimate shows that purchase and use of a simulator would cost 38 percent as much over a 15-year period as it would for an actual equipment trainer.

3. Maintenance simulators are as effective as actual equipment trainers for training maintenance personnel. They cost less to acquire. Therefore, maintenance simulators are cost-effective compared to actual equipment trainers.

4. The data on the cost and effectiveness of maintenance simulators have not been collected in a systematic manner. Therefore, there is no basis at present for making trade-offs between the effectiveness and cost of different types of maintenance simulators on such issues as two-dimensional vs. three-dimensional design, the complexity of maintenance simulators (in such terms as number of malfunctions and instructional procedures), the extent to which simulators should provide a mixture of training in general maintenance procedures and/or for maintaining specific equipment, and the optimum combination of maintenance simulators and actual equipment trainers for training technicians at school.

5. The conclusions to this paper must be qualified by the fact that they are based on limited and often incomplete data. There is a need for data suitable for analyses if comparisons of maintenance simulators and actual

equipment trainers are to be made in the following areas: life-cycle costs, on-the-job performance, and student attrition at school. There is also a need for data if cost-effectiveness comparisons are to be made among simulators that vary in complexity of design, e.g., two- and three-dimensional simulators and types of instructional features.

Acknowledgement

This paper has been approved for public release, distribution unlimited.

References

Cicchinelli, L. F., Harmon, K. R., Keller, R. A., & Kottenstette, J. P. Relative cost and training effectiveness of the 6883 Three-Dimensional Simulator and actual equipment (AFHRL-TR-80-24). Brooks Air Force Base, TX: Air Force Human Resources Laboratory, September 1980.

Orlansky, J., & String, J. Cost-effectiveness of computer-based instruction in military training (IDA Paper P-1375). Alexandria, VA: Institute for Defense Analyses, April 1979. (AD A073400).

Orlansky, J., & String, J. Cost-effectiveness of maintenance simulators for military training (IDA Paper P-1568). Alexandria, VA: Institute for Defense Analyses, August 1981. (AD A108717).

Biodynamic Modeling of the Maintainer

E. R. Winkler
J. T. Miller

McDonnell Douglas Corporation
St. Louis, Missouri

The Maintenance Action Model (MAM), McBride and Lambert (1982), is one component of the U.S. Navy Design-for-Maintainers program. The MAM consists of a set of conceptual tools that can be used by designers to ensure that man-machine interfaces are considered in all phases of equipment design from conceptualization to retrofit. One requirement of the MAM is the incorporation of a biodynamic strength model.

The desire of industry, largely sponsored by the National Institute for Occupational Safety and Health (NIOSH), to achieve a safer workplace for individuals handling materials has greatly accelerated the recent development and validation of biodynamic strength models. The development and incorporation of these types of models into the maintenance design process would complement and extend current design guidelines such as Military Standard 1472C. Specifically, a biodynamic strength model could extend current strength limitation guidelines to account for:

- the female population
- a larger number of body positions than are defined by current guidelines
- a mechanism for defining limits in design-specific or restricted workspaces
- tasks which require extended exertion, i.e., define fatigue limits
- tasks which require repetitive actions
- a mechanism for defining limits for unique or design-specific body positions
- tasks with dynamic as well as static (isometric) requirements.

Applications and Existing Models

Experience with the F/A-18, F-4, AV-8B, and MDC missile systems indicates that a biodynamic strength model could have significant impact in a number of areas. A primary consideration is the need to acquire the fifth and ninety-fifth percentile strength limitations for a wide variety of body positions. A usable biodynamic model could provide this information in a timely and cost-effective manner by eliminating the need to construct mockups

or simulators. This could be directly applicable to VTX. It is especially important that this information be available for the female population, since more females will be employed in maintenance specialities in the future (Report NRAC 80-9).

Our experience has demonstrated a requirement for a biodynamic strength model that can be used to predict strength limitations when design considerations dictate a restricted workspace which may force maintenance personnel to assume unique body positions. Restricted workspaces may also require maintainers to move or lift materials through nonoptimal paths.

We have also found that a biodynamic strength model must either incorporate, or accommodate the incorporation of, procedures for predicting the limits of fatigue when various repetitive tasks are performed. These problems have been most frequently identified in the test and evaluation phase of the F/A-18 program.

Additionally, there is a need for a biodynamic strength model which can predict strength limitations for various hand functions. Specifically, prediction techniques for grasp strength, twisting strength (either with the hand or just the digits), and whole hand or digit pushing and pulling strength limitations are required. The whole-body biodynamic strength model must either incorporate, or be easily modified to incorporate, hand strength prediction features.

Recent requirements of various industries with extensive materials-handling occupations have resulted in the development of a number of biodynamic strength models. We reviewed those models to determine if any could be adapted for use with a weapon system like the F/A-18. Three different modeling approaches have been used--physiological, psychophysical, and biomechanical. These models have been developed from basic precepts that vary widely, and this has influenced the domain of strength-related questions to which they have been applied.

Physiological models have been concerned primarily with repetitive tasks and the levels of exertion that result in various levels of fatigue. Fatigue effects are generally reflected in changes in the rate of oxygen consumption, heart rate, and rate of metabolic energy expenditure.

The psychophysical approach is primarily empirical. Individuals are required to lift, lower, push, pull, or carry objects based on nominal or standard body positions (postures). Voluntary load limits are obtained and are incorporated into a data base which can be analyzed using multiple regression techniques. These analyses generate a model in which various physical characteristics and voluntary forces are entered as a basis for strength predictions.

Biomechanical models have been developed to examine the forces that are exerted on various body components when the body is treated as a purely mechanical structure. This type of analysis examines each body segment which includes the joints, muscle groups, and centers of mass, and then computes the forces and moments that result from loads imposed on the body. Strength limitations are defined on the basis of the structural damage which would occur if various load limits were exceeded.

Evaluation of Current Models

Survey Methodology

An initial survey of the literature on strength modeling indicated that three major university laboratories are working in this area, specifically:

- University of Illinois--Chicago Circle (Illinois), physiological modeling
- Texas Technological University (Texas), psychophysical modeling
- University of Michigan (Michigan), biomechanical modeling.

A questionnaire addressing major issues related to biodynamic strength model requirements was prepared. Questions concerned with the structure and properties of the models were developed on the basis of the preliminary search of the literature. Questions concerned with the user requirements were developed with the assistance of human factors specialists responsible for maintenance design on a variety of aircraft and missile programs (F/A-18, F-15, AV-8B, Harpoon). The questionnaire was forwarded to cognizant individuals at the Illinois, Texas, and Michigan laboratories.

We then visited each of the laboratories and interviewed model developers, individuals responsible for the day-to-day operation of the laboratories, and the graduate students. These discussions centered on model structure and user considerations. The questionnaire was used as a basis for our discussions, but the discussions were not restricted to questionnaire items.

Model Considerations

Adequacy of the model in meeting potential user requirements was a principal concern. The underlying assumptions used to develop each model were considered important, since these included anthropometric considerations and the range of body positions incorporated within the model. The methods of extrapolating to other body positions were also of primary concern, as was the ease of adapting the models to predict body and limb movement, restricted workspace considerations, and repetition and fatigue effects.

User Considerations

The most critical user considerations focused on the current operability of the model and the ease with which new body positions could be added. Additionally, minimal input requirements, such as the weight of the object to be lifted, carried, pushed, or pulled, and the initial and terminal position, seemed desirable. The type of output and time required to obtain it were also important considerations, as was the capability of the models to deal with body position or workplace restrictions. Finally, the ease of making the model compatible with a computer aided design (CAD) system in the future was considered.

Conclusions and Recommendations

We concluded that the technology is available at this time to develop a strength model that can be used in the design phase of system development or to answer basic strength questions for existing systems. This conclusion was

based on the responses to the questionnaires, our examination of the facilities, and the discussions with the individuals at those facilities. The model/design aid could be made to handle questions related to the full range of male and female populations in various work positions. Confined spaces, clothing encumberances and environmental effects could also be accounted for by modifying current biodynamic strength models. This type of system could give rapid and accurate inputs to the designers when the inputs are really required, i.e., early in the design process; and it could reduce the need for redesign.

As other investigators have noted, comparative evaluation of the three models is difficult because the basic assumptions underlying the models are dissimilar (Garg & Ayoub, 1980; Ayoub, Mital, Asfour, & Bethea, 1980; Ayoub, Mital, Bakken, Asfour, & Bethea, 1980). There are also differences in how the models are constructed, and procedures and personnel used to develop reliability and validity estimates which preclude straightforward comparisons. All models reflect the competence of the developers; and selection could not be based on the central assumptions of the models since all have been validated within constraints noted above. There seem to be no inherent reasons why one methodology, psychophysical or biomechanical, should prove superior to the other.

User interface requirements appear as a more useful class of criteria for selecting a biodynamic strength model. The selection of a model that is sensitive to user needs would provide a tool immediately useful to the U.S. Navy and MDC. The University of Michigan model is the most user-responsive model. It requires limited input information and minimal computer skills of the user, and produces graphic depictions of the final posture as one type of output. Therefore, a portion of the software required for integration of the model into a CAD system already exists. MDC could adapt this model to accommodate unique body positions and tasks, and to add repetitive tasks and fatigue effects to fulfill the user requirements that MDC has identified.

References

Ayoub, M. M., Mital, A., Asfour, S. S., & Bethea, N. J. Review, evaluation, and comparison of models for predicting lifting capacity. Human Factors, 1980, 22, 257-269.

Ayoub, M. M., Mital, A., Bakken, G. M., Asfour, S. S., & Bethea, N. J. Development of strength and capacity norms for manual materials handling activities: The state of the art. Human Factors, 1980, 22, 271-283.

Department of Defense. Human engineering design criteria for military systems, equipment and facilities (MIL-STD-1472C). Washington, D.C.: Author, May 1981.

Garg, A., & Ayoub, M. M. What criteria exist for determining how much load can be lifted safely? Human Factors, 1980, 22, 475-486.

McBride, D. K., & Lambert, J. J. Human factors in designing for the maintainer (HFTM-1982-001). Warminster, PA: Naval Air Development Center, January 1982.

Naval Research Advisory Committee, Office of the Assistant Secretary of the Navy (Research, Engineering and Systems). Man-machine technology in the Navy (NRAC 80-9). Washington, D.C.: Author, December 1980.

Comparing Engineering Psychology and Industrial Engineering Approaches to Logistics Problems

Robin L. Keesee

University of Louisville
Louisville, Kentucky

The Issues

The Question

When the opportunity to speak at this meeting was first presented, the suggestion was made that the paper could be on methodological concerns rather than a reporting of experimental results. This was met without great enthusiasm because there had been no notable "visions" to be shared. But, after that exchange and in the midst of some contracted management engineering studies, there was the realization that although the management engineering work was being undertaken within an organization that was purely industrial engineering, the strictly industrial engineering methods were inadequate and the methods used were actually a hybrid of human factors and industrial engineering.

Indeed, after participating in several efforts that were similar to logistics studies, none could be recalled that had been performed entirely with the methods that were to be found in either a human factors, or an industrial engineering curriculum. Perhaps the reason why defense logistics has not been properly served by human factors is because the traditional human factors methodologies are not appropriate to logistics problems. This possibility led to the decision to deliberately consider methods for man-machine or human factors studies in logistics.

Human factors and industrial engineering have been around for thirty years or more as recognized professional disciplines. If this is the case, why is defense logistics in such a poor state from a human factors point of view? Are there some basic characteristics of the disciplines that could explain this state? While this issue could possibly be reduced to a formal hypothesis and tested empirically, this paper will depend on some limited literature references and on personal introspection and, very likely, rationalization by the author.

As a vehicle for the discussion, engineering psychology and industrial engineering will be used as extremes whose approaches to logistics problems will be compared. Hopefully, the contrast in their approaches will be enlightening.

Note that logistics will be used here as "the procurement, maintenance, and transportation of military material, facilities, and personnel" (Websters, 1965, pp. 497). Maintenance and, so, maintainability, is explicitly part of this common definition. The discussion will refocus on maintainability in the conclusions.

Basis for the Question

There are several reasons for approaching the issue of human factors problems in logistics in this manner. First, human factors work is usually at the interface between man and machine and requires knowledge in both directions. That is, knowledge is required of both engineering and psychology. Evidence of this union of two traditional disciplines is seen in the membership of the Human Factors Society (HFS) where 55 percent of the members are psychologists and 16 percent are engineers (Knowles, 1981). No other academic speciality exceeds 10 percent of the membership. Within psychology, more members report their academic training as having been "general psychology" than other specialities (Table 1). Note in the table that the majority of HFS members trained in psychology have doctorates.

For the contrast with engineering, engineering psychology was chosen as the psychology specialty for two reasons: First, it is the name used by psychologists in the early American writing on human factors as a self-descriptor. And second, if we admit that human factors is a hybrid of engineering and psychology and not purely either, then engineering psychology is the specialty within psychology that best represents the knowledge of human performance relevant to the design of the man-machine interface. Here, engineering psychology is not synonomous with human factors.

To match engineering psychology, it appears that industrial engineering is the appropriate one of the major engineering disciplines to represent engineers in this comparison. From the time of Frederick W. Taylor and Frank and Lillian Gilbreth, industrial engineers have been concerned with material movements and work methods (Blair & Whitston, 1971, pp. 11). One could say that the industrial engineer is concerned with the engineering of the civilian equivalents of logistics systems. Industrial engineering is the academic background of a plurality of the members of the HFS identified as engineers (Table 1), but in contrast with psychology, most of the engineers who are HFS members have the masters as the final degree, again a plurality.

A final preliminary observation is in order whose relevance will be shown in the conclusions. Automation makes more control functions possible and allows control with greater accuracy for the same labor, and captial investments and permits the networking of previously independent entities. This automation makes systems more complex. As complex systems are installed

Table 1

Academic Training of Psychology and Engineering Members of the Human Factors Society (Knowles, 1981, p. 145)

	By Speciality		By Degree	
Psychology	General	25.7%	Bachelor	7.1%
	Experimental	18.3%	Master	16.7%
	Industrial	4.2%	Doctor	30.8%
	Engineering	2.7%		
	Other	3.7%		
		54.6%		54.6%
Engineering	Industrial	5.9%	Bachelor	4.6%
	Electrical	2.1%	Master	7.1%
	Mechanical	1.9%	Doctor	4.2%
	Aero	1.3%		
	Other	4.7%		
		15.9%		15.9%

and become operational, they are likely to partially fail but continue to operate at a reduced performance level. Because of the high investment in these systems, project managers are increasingly likely to attempt to improve existing systems rather than undertake design of a new system.

Again, the objective of this paper is to compare engineering psychology and industrial engineering approaches to logistics system problems as a way to identify the causes of human factors problems in current systems that may be organic to the human factors discipline. The general form of each approach, the academic foundations of each approach, and the relative strengths and weaknesses of each will be considered in turn.

Engineering Psychology

The Stereotypical Approach

It is believed fair to say that the usual approach of engineering psychology to logistics problems would consist of the following steps:

1. Introduction to (logistics) application area.
2. Identify (and accept) likely personnel subsystems problems.
3. Propose (and accept) candidate solutions.
4. Design and conduct solution evaluation experiments.
5. Present concluding recommendations.

The initial step is in agreement with Davis and Behan (1962, pp. 490) who are the only authors identified who recommend, even implicitly, that engineering psychologists may be required to study large, complex systems during operation. Their approach is experimental and they provide guidance on the conduct of an experimental program involving large scale systems although their guidance does not explicitly mention the steps just given.

During the initial study phase where some system familiarity is gained, the investigating engineering psychologist is likely to receive, either spontaneously or at his query, suggestions from systems managers or operators that training, selection, work station design, etc., is a problem. Once the personnel subsystem problem is identified, the engineering psychologist develops alternatives that may solve the problem, and proposes experimental evaluation of the proposed solutions. Based on an inferential statistics test of the results, the engineering psychologist makes recommendations about whether the solution is adequate or whether more development is needed. If it is agreed that this is the stereotypical approach, why do stereotypical engineering psychologists behave in this manner? Looking at the foundations for this approach may help answer this question.

Foundation of the Approach

Definitions. To begin at the most simple level, consider the definition of engineering psychology. A common definition of the parent, psychology, is that "psychology is the science of behavior" (Gagné & Fleishman, 1959, p. 1). McCormick (1970, pp. 3) brings the definition closer by saying that human factors engineering is the "process of designing for human use." In attempting to partition the psychologies relevant to systems, de Greene (1970, pp. 44) states that "Engineering psychology...is mainly concerned with the design of equipment, facilities, and environments to match the capabilities and limitations of people." To combine these three, engineering psychology will be defined here as the science of human behavior relevant to the design of the man-system interface where systems may be any combination of hardware, software, and personnel.

The clear understanding in these definitions is that the expected context of engineering psychology applications is the design of new systems.

Education. One way to look at the tools of inquiry and analysis that are the property of an engineering psychologist is to see what tools are provided through his education. If the assumption is made that those practicing engineering psychology are represented in the HFS membership, it will be recalled from Table 1 that the majority of psychologists have the doctorate. That is the education program that will be considered.

Doctoral programs in engineering psychology typically consist of significant course work in three or four primary areas. The first of these might be called engineering psychology itself: courses giving the knowledge of human behavior relevant to the design of hardware. These would include sensory, perceptual, and cognitive processes, and perhaps work or exercise physiology and engineering anthropometry. The second major area would be inferential statistics and would include hypothesis testing, analysis of variance, nonparametric statistics, and very likely one or more advanced topics such as multivariate analysis or response surface methodology.

The final two areas of commonplace emphasis are less standard in structure. Most programs have one or more courses on methods of psychological research, experimental methods, psychological scaling, psychophysics, etc. Last, in programs that vary significantly from experimental psychology by specializing in engineering psychology, there will probably be a few courses

on human factors involvement in design of complex man-machine systems covering task analysis, function allocation, qualitative and quantitative personnel requirements information (QQPRI), and maybe overviews of selection and training within the context of the research, development, and initial fielding phases of the life-cycle of the hardware system.

The thrust of the undergraduate and early graduate psychology education is on explanation of human behavior frequently using qualitative models with much of the later instruction keyed to classical experimentation. The extension of this thrust in later graduate education is on procedural and analytical tools necessary for experimentation.

Observations on Performance

In the three full decades that engineering psychologists have been part of defense R&D, there has been a steady stream of new systems. In these developments, engineering psychologists have made recommendations to improve system performance or to avoid poor performance. Often, no objective evidence was obtained to validate the worth of the recommendation in the end product but survival of the discipline within the defense community suggests a net positive benefit.

In defense logistics, however, there have been no, or few newly developed systems on which engineering psychology could be employed or that could be used to fund advances in the state of the art. Indeed, defense logistics is composed of operating, not developmental systems--systems that are working even though perhaps not as desired or not at full potential.

The advantage the engineering psychologist has in working on logistics systems over weapon systems is that the logistics systems work in peacetime, making observation and data collection during operation feasible while combat weapons systems do not, although the logistics systems' peacetime volume and environment is probably dissimilar to its wartime situation. The engineering psychologist's chief disadvantage in addressing logistics is that there are few "clean sheet of paper" developments on which his design oriented tools could be applied.

If the engineering psychologist took the view of a unit mechanic rather than a new hardware development project manager's view (i.e., M-1 tank or F/A-18 aircraft), then task analysis, a design oriented engineering psychology tool, could be usefully applied to a logistics system.

Overall, engineering psychology has apparently performed well in design of new systems but has been less effective in logistics.

Case Studies from Engineering Psychology

In the author's experience, there are three significant studies that involved efforts to improve systems that were complex and that were operating. Two of these were in settings close to engineering psychology and one was in an industrial engineering environment. The methods used in these studies, and their success, speak to the current issues.

Case study--NYCMTA. Several incidents and accidents in 1970 had apparently been poorly handled by the senior operations supervisors of the New York City subway, leading to some traumatic experiences. In late 1970, the executive management of the subway division of the New York City Metropolitan Transit Authority (NYCMTA) invited a group of faculty from Virginia Polytechnic Institute initially to develop a remedial training program for these senior operations supervisors, the Desk Trainmasters. In an initial consulting effort, the faculty group, all but one of whom were psychologists and none of whom were industrial engineers, became familiar with the operations environment, collected and analyzed performance data, and provided a comprehensive list of recommendations not limited to training (Snyder, Wierwille, Sgro, & Torgersen, 1972). There were several significant parts to the data collection and analysis program. A task analysis was conducted for the Desk Trainmaster position using communications recordings from past emergency incidents as the scenarios. A human engineering review of the communications and information storage and retrieval equipment was conducted. Trainmasters were interviewed for their opinions on training requirements, information necessary in emergencies, and strategies for resolving emergencies. Finally, a time study through the a.m. and p.m. rush hours was conducted to determine task loading in nonemergency situations, time and error performance in communications tasks, and the extent of nonelectrical communications within the command center.

To be doctrinaire, one could classify task analysis, interviews, and human engineering reviews as being from engineering psychology, and the time study as being from industrial engineering.

More interesting, approximately ten man-weeks of time from professionals (18 if time of BS-Engineering graduate students were included) were devoted to studying the situation to identify the human behavioral problems and to estimate their relative magnitude. Once the specific problems were identified, approximately four professional man-weeks were spent in the solution implementation phase although more than 24 man-weeks of technician resources were committed in this phase. Given a total manpower expenditure of 46 man-weeks, 22 percent of these were professional (39 percent if the 8 man-weeks of BS-Engineers are counted) and were spent identifying the specific problems. Of the total professional expenditure of 14 man-weeks (or 22 man-weeks), 71 percent (or 82 percent) were devoted to figuring out what the problem was with the remainder devoted to supervising solution implementation which was the longer phase from a calendar view.

Case study--Army repair parts supply. A study less equivocally in logistics was one conducted by the U.S. Army Human Engineering Laboratory (HEL) that sought to resolve human performance problems in the retail repair parts supply system (Keesee, Camden, Powers, Kilduff, Hill, Gombash & Sarli, 1980). Being within the HEL, the study was in an engineering psychology environment. Data were collected using three general methods. Time studies were made of repair parts clerks to learn job content, task load, and task time and error performance, and to gain detailed familiarity with the jobs to help uncover possible work methods improvements. Structured interviews with the clerks, their supervisors, and technical and operations managers were held to gain their opinions of sources of problems and the perceived distribution

of time among tasks. Finally, a simulation model was developed of the repair parts request paper work and part flow from the customer units through the Division and to higher echelons. This model was intended to be a good framework for the collected data and a guide to the limits and bottlenecks on system performance.

Of the methods used, the structured interview and associated content-type analysis were from engineering psychology while the time study and the simulation were from industrial engineering. As in the first case study, a look at the resource phasing may also be instructive. Of the approximately 108 man-months, 78 (72 percent) were in the study phase where study team members became familiar with the system, devised and implemented a data collection and analysis plan, and finally identified specific problems in human behavior and performance terms. The remaining 28 percent of the effort was in developing the recommended redesign of the system.

Summary

If the admittedly limited evidence is accepted, it has been observed to this point that engineering psychology has its roots deeply in experimentation which is comparative by nature, that most of the professional time in a study of a logistics system is spent on determining the narrow identity of the problem and much less time is spent on designing solutions, and that investigation of systems in operation may employ data collection methods not all of which are classically engineering psychology.

Industrial Engineering

The Stereotypical Approach

Faced with a military logistics assignment, the industrial engineer will probably go through the following steps:

1. Introduction to (logistics) application areas.
2. Identify likely areas of inefficient operations.
3. Collect and analyze time performance and cost data.
4. Develop and evaluate alternative solutions.
5. Recommend and justify solution.

In the first step, the industrial engineer would become familiar with the operations to be studied helped somewhat by the similarity to civilian industry. Instead of trying to stimulate discussion with supervisors and workers about methods of selecting and training the operators as might the engineering psychologists, the industrial engineer is likely to inquire about the lengths of queues, workload fluctuations, work planning and scheduling, etc.

After gaining familiarity with the overall operation, the industrial engineer will probably choose one or two situations that appear to be inefficient because of being labor intensive or duplicative, having extensive static inventory, having idle workers or equipment, or having lengthy waiting times for customers. Once a problem area has been identified, time and cost data will be collected and analyzed. Alternatives will then be developed and

cost and time performance for these will be estimated. A solution will then be recommended with quantitative evidence that the recommended solution is the best of the alternatives and significantly better than the current methods.

Foundation of the Approach

Definitions. With the first separate academic industrial engineering departments formed in 1908 at Penn State and Syracuse (Turner, Mize, & Case, 1978, pp. 22), industrial engineering is a little older than engineering psychology. In 1955, the American Institute of Industrial Engineers agreed upon a definition:

> Industrial Engineering is concerned with the design, improvement, and installation of integrated systems of men, materials, and equipment. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences together with the principles and methods of engineering analysis and design to specify, predict, and evaluate the results to be obtained from such systems (Turner, et al., 1978, pp. 21).

Note that industrial engineering is the only major engineering discipline to explicitly include people as a component of the design process. Also, at least the definition refers to systems improvement as well as design.

Education. Since the HFS directory indicated that more industrial engineering members had masters degrees than had doctorates, that will be the degree program considered.

Besides the basic mathematics and science requirements of the early undergraduate processes, the industrial engineer will have required courses in the major discipline in four or five categories with a few possible electives. Most fundamental would be a course in methods engineering covering time studies, activity charts, work sampling, synthetic motion time systems, etc. Similarly fundamental would be courses in accounting and economic decision making. At the intermediate level would be human behavior in organizations, a survey of engineering psychology, and possibly work physiology. Inferential statistics would be taught in two or more courses that would consider hypothesis testing, analysis of variance, regression, and quality control. Coursework in operations research would cover queueing, facilities layout, scheduling, inventory and other process models, optimization, mathematical statistics, and digital simulation.

At the masters level, additional courses in the process models, simulation, mathematical statistics, and the mathematics underlying operations research would be taken if operations research were the major. Manual control, safety, display design, human factors in design of complex systems, and more inferential statistics courses would be taken by human factors majors.

The thrust of the undergraduate and early graduate industrial engineering education is primarily in quantitative solutions to problems especially problems involving time, costs and stochastic variables. A secondary emphasis is in management of technical or manufacturing operations. There is little emphasis on seeking understanding of underlying processes unless a quantitative relationship among events is expected.

Observations on Performance

The Accrediting Board for Engineering and Technology (ABET) insures that academic programs maintain a balance in course content between industry's typically immediate needs and academicians' perceptions of what will be needed by the engineer practicing over the next ten to thirty years. The continued demand for graduates suggests that industrial engineers are being adequately trained to meet industry's needs for quantitative management staff.

In defense logistics, the BS/MS general industrial engineer is likely to do well at improving worker task performance including maintenance tasks. The industrial engineer's training would directly apply to synthesizing and simplifying maintenance and operating tasks where hardware does not yet exist and to perform time and motion studies where hardware does exist. This latter work would be of the nature of that reported by Theisen and Hsu (1982) as secondary to their research study. The BS/MS IE often spends the first year or two out of school in methods of work simplification. Such an engineer would consider methods improvement and simplification of maintenance tasks to be a routine and unremarkable application of his skills.

However, the IE, without a specialization in human factors at the MS level, is unlikely to have a highly developed global view of the systems. That is, without one or more courses concentrating on interactions within elements of the personnel subsystem, the BS/MS IE is prone to concentrate on improving the efficiency of system or process subsystems, treating the humans as an incidental randomly behaving component.

A Case Study from Industrial Engineering

Recently the U.S. Naval Ordnance Station-Louisville asked the Department of Industrial Engineering of the University of Louisville for assistance in conducting management engineering studies of a collection of service functions such as custodial service, administrative telephone operations, vehicle operations and maintenance, etc. The objective of the studies was to improve labor and material efficiency in each function.

The methods of study selected by the faculty group leading the effort were structured interviews to gain worker and supervisor opinions about the current nature of the work and possible improvements, review of accounting information, work sampling in functions where workers had fixed work stations, and a modified time study in all areas that was similar to what Mundel (1978, pp. 94) called work activity analysis. This modified time study sought to determine the job content, to make some estimates of the accuracy of accounting information, and to force the analysts to gain great familiarity with the job in order to identify methods improvements.

Obviously, the time study, work sampling, and use of accounting data are classical industrial engineering tools while the structured interview is more in the engineering psychology direction. Looking at phasing of resources, it appears that seventeen man-months of professional time will be expended in identifying areas of inefficiency or problems with perhaps eight man-months spent in developing specific, implementable recommendations.

Summary

From the review of the industrial engineer's education and one limited example, it appears that this discipline is trained to solve defined problems involving randomly varying costs, operations volumes, and times quantitatively. More time will be spent by the industrial engineer in defining the problems than in developing a solution.

The Comparison

Results

Given training in the human factors methods appropriate to design of a complex man-machine system, function allocation, task analysis, QQPRI, etc., the engineering psychologist will have a whole system perspective. This view may, however, be focused on the personnel subsystem and only dimly include overall logistic systems performance. The industrial engineer will be more concerned with improving one subsystem at a time but would use the impact of the recommended solution on the total system cost, time, or other quantitative performance measure to justify acceptance of the recommendation. The industrial engineer would be able to make improvements in the physical work place but would tend to not recognize the human information processing limitations that the engineering psychologist would note. It would appear that neither engineering psychology nor industrial engineering is directly appropriate to logistics studies although both are useful training for the field. Neither is complete.

Discussion

Basic approaches of engineering and psychology vs. logistics studies. In the comparison above, stereotypical approaches to logistics problems were hypothesized for engineering psychology and industrial engineering. Consider their approaches to their natural work. Virtually every introductory or intermediate engineering text includes some version of the engineering problem solving process. Krick (1962, pp. 15-20) lists several. A typical version of the engineering approach to problems is:

1. Define problem.
2. Define constraints.
3. Develop alternatives.
4. Evaluate alternatives.
5. Decide and implement.

The formal research process in engineering or experimental psychology could be represented by the following steps:

1. Define hypothesis.
2. Design and conduct an experiment.
3. Analyze results.
4. Generalize results from experiment to at least the hypothesis.

Both of these approaches begin with what is, in effect, a statement of the objective. In light of the three case studies, it seems that stating the

initial step so blithely gives little credit to the difficulty of the task. In each of the three, the vast majority of the work effort was in defining problems that were solvable. Logically, the steps that are undertaken in logistics studies should reflect the necessary sequence of progress in the work. A reasonable sequence might be the following:

1. Diagnosis.
2. Define limiting factors.
3. Select problems.
4. Solve with appropriate technical discipline.

There will be, in the future, an increasing rate of requests for human factors assistance to help improve logistic systems as well as to help improve operational performance of other complex systems that have already been designed and fielded. The first step in these efforts is properly entitled diagnosis and represents the gathering of valid performance data, and the analysis of these data for comparison with norms, standards, specifications, and expectations to arrive at the precisely stated problems that are amenable to solution.

The second step, one that begins midway through the diagnosis phase, is the listing of all of the problems or circumstances that hinder system performance, the limiting factors. Items on this list should then be objectively evaluated for effect on system performance. Those that are the most significant and are capable of being solved within available resources should be selected and solved by whatever technical discipline is appropriate.

Methodology considerations in logistics system diagnosis. Several things of varying importance have been learned in the experiences reported above concerning diagnosis of logistics systems. First, a quantitative model of systems operation and performance should be developed beginning early in the diagnosis phase. This model will serve as a guide to determine what operating data should be gathered and, once the data is in hand, the model will serve as a framework for utilization of the data. Also, the model will reflect how well the diagnosticians understand the system operation.

Because operating logistics systems, and to some extent other operating complex systems, frequently have management information systems (MIS) that collect, summarize, and report an abundance of statistics, operational performance data is usually readily available. The diagnostician should accept all offers of such data, and should pursue this source as well as the often more useful data hidden away in the manually kept logs and registers of individual units. The pursuit of these existing data sources and acceptance of all offers will possibly reduce the necessity to independently collect data or will make the data that is collected much more relevant. But a caution is in order here. Since the performance statistics from MIS are very often the basis in part for a career performance rating of operations supervisors and managers, the MIS may be susceptible to manipulation. While useful, the award of credibility of the whole of the MIS results should be reserved until validity of the data can be determined.

The remaining comments on diagnosis methodology are of less importance. In diagnosing problems of a logistics system, opinions of the system users or

operators should be represented. Without their perception of participation, implementation of the results will be thwarted. The individual responsible for conduct of the logistics study should participate in any data gathering or collection to help ensure that the limitations on generalizing of the data results are learned and respected. A last note is that it is unlikely that the quantitative model will be completed within the study schedule but will be useful nonetheless.

Ramifications for professional education. If it is intended that human factors professionals be employed to improve existing, complex, operational systems, then their education, either psychology or engineering based, should reflect the extent to which diagnosis will consume their time in professional practice. Only the engineering psychology subset of psychology terminal degree graduates need be concerned here. But all industrial engineering BS/MS graduates can expect to be asked to attempt improving the whole of a complex system, albeit a civilian system, at some point in their careers. Yet no engineering text has been found that integrates the several individual data collection and analytical techniques into a strategy or set of principles for diagnosis. Alas, the only text where use of industrial engineering techniques for diagnosis of whole, complex systems is even implied is Chapanis (1959). (Methods engineering with its time study and other direct observation techniques is taught in IE curricula in the context of making improvements within a subsystem or component of a system or process.)

The strategy and techniques of diagnosis and the subsequent steps listed above should be addressed in human factors graduate programs and in undergraduate industrial engineering curricula.

Conclusions

Although it is good that elements of the defense human factors community are becoming concerned with logistics problems, it would appear from the abundance of such problems that the service provided logisticians by human factors has been lacking in the past. By comparing the approaches of disciplines on either extreme of human factors, it has become clear that human factors as a technology is oriented toward design of new systems and not toward improvement of systems that are in place and operating. So, it is plausible that one reason that there are significant human factors problems in logistics systems is that most logistics systems are products of evolution rather than new designs and the classical human factors tools do not directly apply.

If this conclusion is correct, several remedies may be undertaken. Clearly, the basic and often academic research that promises improvements in selection, training, job-aid design, and other man-system interface issues for maintainers and other logistics personnel should continue. In structuring efforts to improve a given logistics system, those practicing human factors should resist the temptation to begin comparative or experimental activities until after completing a deliberate diagnosis to identify and evaluate the significance of all of the personnel subsystem problems within the logistics system.

This counsel will apply equally to the nondefense and nonlogistics within defense human factors groups in the future. As the systems within their purview increase in complexity from automation or other sources, and their managements seek improvements in lieu of costly new designs, the need for human factors diagnosis methodologies will be similar to the current needs in defense logistics.

Returning at last to the conference topic, applying the strategy above to maintainability would suggest that maintenance within a service should be studied from a human factors view as a system. For example, field maintenance of tanks might be the study scope rather than maintenance of a new hardware system such as the new M-1 tank. An orientation by the human factors study team toward a particular hardware end-item, an aircraft or a tank, will have a high potential for degenerating into a series of specific fixes. These fixes will be beneficial but the identification of required fixes is not something for which professionals in human factors are typically well trained and will cause them to miss the broad problems that are common across hardware systems and to which the human factors community can make major and unique contributions.

While easily recommended, it is recognized that the current human factors organizations within DOD are not conducive to the application of this diagnosis strategy because of their research orientation. Perhaps their organizational structures can be adapted to permit the practice of human factors application in the suggested manner alongside the research.

The foregoing observations, comments, recommendations, and admonitions may seem to many as gratuitous coming as they apparently do with no more than personal empiricism as their basis. Any future more credibly objective investigation of these issues might formally survey the content of academic programs for relevance to human factors diagnosis, and the frequency of occurrence of various experimental and analytical methods in investigations of complex operational systems reported in the applied journals. Unfortunately, few written reports reveal directly the relative manpower expenditures between narrowly defining the problem and solving it. Until the voids are filled, perhaps the success of this writing will be seen in any subsequent discussion of methodological propriety in logistics studies.

References

Blair, R. N., & Whitston, C. W. Elements of industrial systems engineering. Englewood Cliffs, NJ: Prentice-Hall, 1971.

Chapanis, A. Research techniques in human engineering. Baltimore: Johns Hopkins Press, 1959.

Davis, R. H., & Behan, R. A. Evaluating performance in simulated environments. In R. M. Gagné (Ed.) Psychological principles in system design. New York: Holt, Rinehart and Winston, 1962.

de Greene, K. B. Systems psychology. New York: McGraw-Hill, 1970.

Gagné, R. M., & Fleishman, E. A. Psychology and human performance: An introduction to psychology. New York: Holt, Rinehart and Winston, 1959.

Keesee, R. L., Camden, R. S., Powers, R. M., Kilduff, P. W., Hill, S. G., Gombash, J. S., & Sarli, G. G. Human performance review of the retail repair parts supply system (Vol. I & II). Aberdeen Proving Ground, MD: U.S. Army Human Engineering Laboratory, February, 1980.

Knowles, M. G. (Ed.). The human factors society directory and yearbook, 1981. Santa Monica, CA: The Human Factors Society, 1981.

Krick, E. V. Methods engineering. New York: Wiley, 1962.

McCormick, E. J. Human factors engineering (3rd ed.). New York: McGraw-Hill, 1970.

Mundel, M. E. Motion and time study (5th ed.). Englewood Cliffs, NJ: Prentice-Hall, 1978.

Snyder, H. L., Wierwille, W. W., Sgro, J. A., & Torgersen, P. E. Consultants' report on means for improving the performance of the desk trainmaster. Blacksburg, VA: College of Engineering, Virginia Polytechnic Institute and State University, January 1972.

Theisen, C. J., Jr., & Hsu, S. H. Derivation of maintainability design guidelines: An experimental approach. Paper presented at the Design-for-Maintainers Conference, Pensacola Beach, FL, March 1982.

Turner, W. C., Mize, J. H., & Case, K. Introduction to industrial and systems engineering. Englewood Cliffs, NJ: Prentice-Hall, 1978.

Webster's Seventh New Collegiate Dictionary. Springfield, MA: G & C Merriam, 1965.

Design-for-Maintainers Conference: Summary Comments

Julien M. Christensen

General Physics Corporation
Dayton, Ohio

It is a high honor, indeed, to be asked to comment on what has transpired here the past two days. LT McBride is to be commended for developing such a well-integrated technical program in this significant area. He has taken a systems approach to this important problem and it is important that each contributor keep that in mind. Otherwise, we will fall into the "blind men and the elephant" problem, each feeling that the parameters with which he deals hold all of the answers to the problem. In reality, it is difficult to think of an area in which selection, training, human engineering, environmental considerations--in fact, all of the human factors areas--interact more intimately. We might gently urge that, in addition to his emphasis on the establishment of quantitative relationships between maintenance design principles and cost and readiness, checklists, modeling of the maintainer's role in the system, and the effects of environmental variables (odd hours, long hours, etc.), the interactions of these with selection and training variables be given additional consideration. (If the Navy is like the Air Force, I suspect that this might mean crossing organizational lines. Cross them, LT McBride; please cross them.)

These past two days we have heard papers or comments from the floor dealing with personnel issues, methodological issues, diagnostics, model development, criterion development, and training--quite a menu for a two-day meeting. LT McBride has structured a program whose thrusts encourage interaction among the participants. I feel, also, that he has organized and fathered the first of what will become an annual event--to the benefit of the other Departments of DOD and industry, as well as to the benefit of the U.S. Navy. The good things we have witnessed here have implications for any department or organization that is faced with maintenance of the products of our technological age.

The Age of Technology

Regarding the era of technology, whose threshold we probably have barely crossed (and thus no one is in a very good position to estimate its eventual impact), one wag observed that had it not been for Thomas Alva Edison, all of us would have to resign ourselves to watching television by candlelight!

Several well-known authorities suggest that the adaptive processes of mankind are being strained to the limit by modern technology, even suggesting that the rapid acceleration of technology presages the end of civilization, at least as we know it. But very few want to revert to the living conditions of a pretechnological age.

The U.S. Navy is a prime example of a department that takes full advantage of the latest technological developments and, in fact, is a leader among the agencies that support advanced developments in technological areas. Like the Air Force, where I served for most of my professional career, Naval leaders apparently feel that they must extract every bit of capability from both their people and the products of technology with which those people interact. This is an easy position with which to sympathize because it appears that our potential adversaries are doing the same thing. As human factors specialists, it is our job to apprise our leaders and systems planners and designers of what can be expected from people in the people x machines equations.

This symposium is evidence that the leadership of the U.S. Navy realizes that more attention must be given to the human as a component in the maintenance environment--the design of the equipment, the working environment--all of the factors that are being considered at this meeting. The alternative is technological regression or the acceptance of a maintenance burden that already is reaching levels that preclude new developments, force the Navy to buy two aircraft in order to have one ready to do its job, etc.

Conditions qualitatively similar to this exist in non-DOD pursuits. A comparison of the costs of operating commercial airlines in 1970 versus 1980 may be instructive. (I am indebted to United Airlines for the 1980 figures; I forget where I got the 1970 figures.)

Table 1

Comparative Cost of Commercial Airline Operations: 1970 versus 1980

	1970 (%)	1980 (%)
Maintenance	28	16
Fuel and oil	28	52
Flight crew salaries	17	20
Depreciation & obsolescence	19	9
Miscellaneous	8	3
TOTAL	100	100

The 1970 figure of 28 percent for maintenance is quite similar to that for Navy and Air Force aviation. (Of course, one can also conclude from this table that the way to reduce the percentage of expenditures for maintenance is to raise fuel prices!)

It has been estimated that in 1970 the cost of automotive transportaton in the United States was approximately 160 billion dollars, and of this amount, 22 percent was spent on maintenance. It is further estimated that 40 percent of this 22 percent (or approximately 14 billion dollars) was wasted on unnecessary repairs. We waste more money on our automobiles than the gross income of many countries.

During this same time period, American industry spent approximately 200 billion per year on maintenance and it is estimated that approximately one-third of that amount was wasted. One industrial study showed that corrective maintenance is three times as expensive as preventative maintenance. But before you embark on an industrial program in preventative maintenance make sure that the production manager agrees to your requirements for downtime!

In the American home, the maintenance proportion of the total life-cycle cost of a color television set in 1977 was approximately 35 percent, while a comparable figure for refrigerators was 6 percent. There is a lesson here: the basic technology that supports a refrigerator is relatively simple and has changed very little over the past generation; we have learned how to design refrigerators that are almost maintenance-free. The Navy probably could achieve that dream of a 95 percent in-commission rate for Corsairs today but how would you like to engage a MIG-25 in a Corsair? No, the Navy will continue to take advantage of the latest technology and it is incumbent upon people such as us to provide Naval authorities and those who develop their systems with information that will enable them to integrate man into this complex picture in such a way as to maximize systems effectiveness. That is why this meeting is so important.

Finally, just as there is considerable transfer of technology from the Navy to industry and commerce, it is my belief that what is being learned in this, and related programs, will benefit all of those concerned with the maintenance and other life-cycle cost problems fomented by the products of modern technology.

A Systems Interpretation of This Seminar

I was weaned on the so-called "systems approach" to the design and development of systems. I hope that you will indulge me if I try to interpret what I saw and heard at this conference in those terms.

Figure 1 discloses that people, hardware, and job environment interact, yielding performance that is intended to meet specified system goals. The key term is interaction. It is worth noting that these interactions take place in (and interact with the components of) a "total environment." There is no doubt that what transpires in one's life outside the immediate job environment affects his performance on the job. Hartman, of the USAF School of Aviation Medicine, has shown that one of the very significant factors that determines how well Military Air Command crew members perform is the attitude of their family members toward the disrupting features of their jobs. We undoubtedly would find it advantageous to examine this part of the picture, but it must be done with care since much of it is private and involves other members of the family. However, it is foolish not to recognize that these factors can sometimes be so powerful as to literally overwhelm the factors over which we have more direct control.

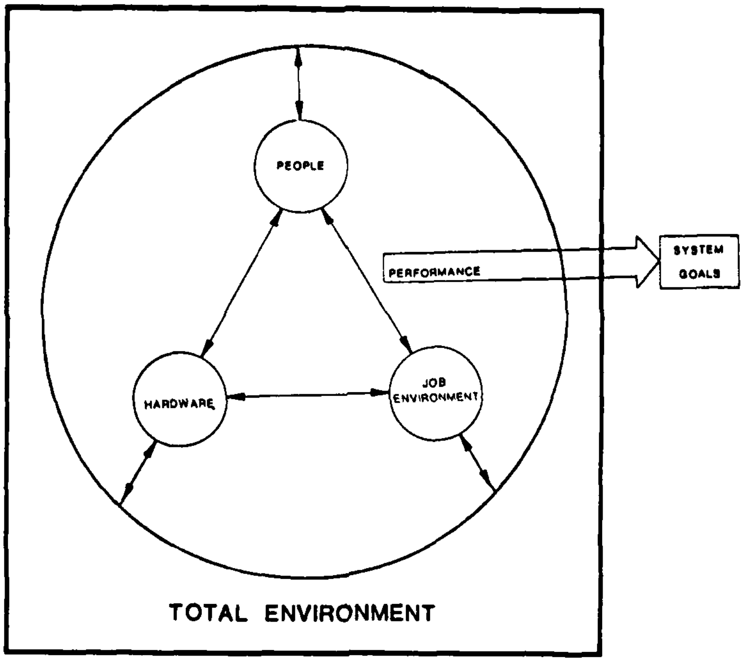


Figure 1. An interactive model of systems performance.

Let us examine a well-known variance model as a way of establishing some sort of a context for this meeting. The formula is:

$$\sigma^2_{Tot} = \sigma^2_{P} + \sigma^2_{H} + \sigma^2_{E} + \sigma^2_{PH} + \sigma^2_{PE} + \sigma^2_{HE} + \sigma^2_{PHE} + \sigma^2_{Error}$$

That is, total systems variance is equal to the sum of the variance attributable to people (P), hardware (H), and environment (E) plus the three first-order interactions and the single second-order interaction. The conference is devoting special attention to:

$$\sigma^2_{PH,}\quad \sigma^2_{PE,}\quad \text{and}\quad \sigma^2_{PHE.}$$

Professor Rouse called our attention to the significant interrelationship between training and human engineering. Thus the σ^2_p term probably should be broken down further to reflect such components as aptitude, education, experience, attitude, and motivation. The possibilities of obtaining significant higher-order interactions in such a situation are very real; unfortunately, we have very little idea of how to deal with them.

Also, we have said very little at this conference about the interrelationships between reliability and maintainability, yet all of us are aware that these interactions are very real and very important. I will only observe that one reliability study showed that only approximately 30 percent of equipment failures were due to poor workmanship while 70 percent were due

to poor design and "careless handling." (I put the quotation marks around "careless handling" because of the implications for design. Something that is designed without handles, is awkward to handle and will probably be "carelessly handled.")

The model helps me, at least, to conceptualize what we are striving to achieve here. It serves also to remind us of significant factors that we may not be considering as primary contributors, and certainly not as interactive contributors. In this particular application, the variance model does little more than this, primarily because we usually don't have a measure of σ^2 Error. This places severe restrictions on significance testing!

The variance model theoretically could handle such detailed structures as Swain's "Performance Shaping Factors" (Swain & Guttman, 1980) but it would become so cumbersome as to be useless. However, an examination of the Swain table (Table 2) serves to remind us how far we have yet to go if we intend accurately to describe and then predict human behavior in complex systems.

Personnel Issues

Dr. Modrick reminded us that we need a better definition of the population for which we are designing--the maintenance population. About all that we ever hear is that, on the average, they have two years of high school and read at a level somewhere between that of a sixth grader and an eighth grader. We know, also, that they have virtually no mathematical skills, that they are not particularly good at integrating information from various sources, and that they hate to post information to forms!

About 15 years ago, when I was Director of the Human Engineering Division of the Aerospace Medical Research Laboratory, we commissioned Harold Leuba to look into these matters a bit. A few of his findings come to mind: (1) Maintenance men have strong preferences as to the troubleshooting techniques they use. One should force a specific technique on them only if it can be shown to be of considerable advantage. (2) Maintenance men have been known to report and remedy nonexistent malfunctions just to improve their track records. (3) Many maintenance men (and operators) have their own favorite malfunctions. Leuba could reduce diagnostic uncertainty by over 50 percent simply by knowing who made the complaint.

The operators, of course, are a party to the current unsatisfactory state of affairs. Some tend to withhold information ("what the hell, they can't fix it anyway"); they offer only sketchy descriptions, glib write-ups, or none at all; some blame nonmalfunctioning equipment for their own deficiencies; some abuse the equipment and yet are willing to blame the maintenance man for its breakdown. The operator-maintainer interaction deserves attention.

The human factors specialist would like to have as complete an inventory as possible of the maintenance population's basic skills, the aptitudes of its members, and, as Dr. Modrick said, perhaps a count of how many are left-hemispheric and how many are right-hemispheric with respect to central nervous system functions. How many are procedures-oriented and how many are principles-oriented? What are their short-term and long-term memory capabilities? Can they assimilate more from three-dimensional drawings than

Table 2

Representative Listing of Factors That Shape Human Performance

EXTERNAL

Situational Characteristics

- Architectural Features
- Quality of Environment:
  - Temperature, Humidity, Air Quality
  - Noise and Vibration
  - Degree of General Cleanliness
- Work Hours/Work Breaks
- Availability/Adequacy of Special Equipment, Tools, and Supplies
- Manning Parameters
- Organizational Structure (e.g., Authority, Responsibility, Communication Channels)
- Actions by Supervisors, Co-workers, Union Representatives, and Regulatory Personnel
- Rewards, Recognition, Benefits

Job and Task Instructions

- Procedures Required (Written or not Written)
- Written or Oral Communications
- Cautions and Warnings
- Work Methods
- Plant Policies (Shop Practices)

Task and Equipment Characteristics

- Perceptual Requirements
- Motor Requirements (Speed, Strength, Precision)
- Control-Display Relationships
- Anticipatory Requirements
- Interpretation
- Decision-Making
- Complexity (Information Load)
- Narrowness of Task
- Frequency and Repetitiveness
- Task Criticality
- Long- and Short-Term Memory
- Calculational Requirements
- Feedback (Knowledge of Results)
- Continuity (Discrete vs Continuous)
- Team Structure
- Man-Machine Interface Factors:
  - Design of Prime Equipment, Test Equipment, Manufacturing Equipment, Job Aids, Tools, Fixtures

STRESSORS

Psychological Stressors

- Suddenness of Onset
- Duration of Stress
- Task Speed
- Task Load
- High Jeopardy Risk
- Threats (Of Failure, Loss of Job)
- Monotonous, Degrading, or Meaningless Work
- Long, Uneventful Vigilance Periods
- Conflicts of Motives about Job Performance
- Reinforcement Absent or Negative
- Sensory Deprivation
- Distractions (Noise, Glare, Movement, Flicker, Color)
- Inconsistent Cueing

Physiological Stressors

- Duration of Stress
- Fatigue
- Pain or Discomfort
- Hunger or Thirst
- Temperature Extremes
- Radiation
- G-Force Extremes
- Atmospheric Pressure Extremes
- Oxygen Insufficiency
- Vibration
- Movement Constriction
- Lack of Physical Exercise

INTERNAL

Organismic Factors

- Previous Training/Experience
- State of Current Practice or Skill
- Personality and Intelligence Variables
- Motivation and Attitudes
- Knowledge of Required Performance Standards
- Physical Condition
- Attitudes Based on Influence Of Family and Other Outside Persons or Agencies
- Group Identifications

they can from verbal description? What is the optimal mix of verbal and illustrative materials for this population?

Task analysis can provide information that relates to some of the above issues. We have found summary classification of behaviors, such as that shown in Table 3, helpful in the interpretation of the results of task analyses (Berliner, Angel & Shearer, 1964).

We find that a very complete task analysis can be developed by the use of video cameras, the General Physics Performance Measurement System (essentially a system for recording all motor responses), and a record of all communications. Unfortunately, cognitive-type activities usually have to be inferred from overt activities and communications, supplemented by interviews with those being observed.

Finally, the characteristics of populations such as the maintenance population of the U.S. Navy are probably always changing. Perhaps there are ways of forecasting what those characteristics will be eight to ten years into the future when a system that is now in the conceptual stage will be operational. If there are such methods, I am not familiar with them. But we do have moderately good methods for predicting what skills will be needed to maintain a system some time before it is operational and we should exercise these. The forecasting of skill requirements and the development of selection and training programs to insure that those skills exist in the proper number at the right time is complementary to our program of design for maintenance.

Methods and Procedures

It has been said that any branch of science or engineering makes progress largely as a function of its methods. Human factors is no exception. I will briefly examine a sampling of the methods referred to by participants of this conference.

Activity Analysis

Activity analysis covers an entire family of methods whose objective is easy to state but whose execution is difficult. The term simply refers to the gathering (recording) and analysis of what people are doing. Modern methods of picture taking (e.g., video cameras), response recording (e.g., the GPC Performance Measurement System), and recording of communications have made it possible to define stimulus and response conditions fairly well in almost any situation. The nature and interpretation of cognitive activities still depend heavily on inference and individual interpretation.

Task analysis is currently the preferred method of activity analysis, at least in DOD. I agree, however, that much work needs to be done to make task analysis more useful.

Using the equipment mentioned in the previous paragraph, one can usually prepare a very satisfactory task analysis. However, as Inaba suggests, there are problems associated with the use of task analysis. These include (1) a tendency to gather an enormous amount of data, often without a clear idea as to how it will be reduced, or, sometimes, even why it is being gathered, (2)

Table 3

Classification of Behaviors

Processes	Activities	Specific Behaviors
1* Perceptual Processes	*.1 Searching for and Receiving Information	Detects Inspects Observes Reads Receives Scans Surveys
	.2 Identifying Objects, Actions, Events	Discriminates Identifies Locates
2 Mediational Processes	.1 Information	Categorizes Calculates Codes Computes Interpolates Itemizes Tabulates Translates
	.2 Problem Solving and Decision Making	Analyzes Calculates Chooses Compares Computes Estimates Plans
3 Communication Processes		Advises Answers Communicates Directs Indicates Informs Instructs Requests Transmits
4 Motor Processes	.1 Simple/Discrete	Activates Closes Connects Joins Moves Presses Sets
	.2 Complex/Continuous	Adjusts Aligns Regulates Synchronizes Tracks

<u>Note</u>. Berliner, et al., 1964

*Numbers inserted to facilitate tabulation of data.

interpretation difficulties (see our earlier comments regarding the use of the Berliner code), (3) assurance that the sample is representative of the population. Someday, someone will do a study on the independence of task elements and find, as K. U. Smith did a generation ago with respect to therbligs, that they are not independent; that one, therefore, must at least recognize that they are not additive, and that different orders of execution yield different results. This doesn't invalidate the technique; it does suggest care in interpretation. Finally, as Dr. Modrick observes, the proper role of task analysis in the design process has yet to be satisfactorily defined.

Failure Analysis

There are numerous methods aimed at the identification of error-likely loci in systems. Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) are two that have been mentioned at this meeting. I'm sure that these are useful techniques; I would feel more comfortable if someone would show me data demonstrating their reliability. One study at Perceptronics suggests that different people obtain rather different results when developing FTAs. This doesn't mean that such analyses are not useful; it does mean that we have an obligation to search out and carefully define the limitations of the tools that we employ.

"Go to the Field"

I very much admire the point of view and approach as demonstrated by Theisen and his group, by Orlansky, by Inaba, by Schmitt and others. They recognize that there are enormous benefits to be derived from gathering data under actual operational conditions or trying systematically to extract useful information from vast data stores. We often underestimate the incredible fund of information that exists "out there." In addition to serving as a source of data for immediate application, it can yield direction for future supporting research.

"Going to the field" often means resorting to the use of techniques such as questionnaires, interviews, and rating scales. I'm happy to report that "opinion" is becoming psychologically respectable as a source of data. Interestingly, it was the engineers, with techniques such as Delphi and the Cooper-Harper scale, who drew attention to the value of these tools.

Confirmatory Methods

When I am confronted with a situation in which it is obviously going to be difficult to obtain hard, objective data, I try to use at least two methods to address the same hypothesis. Thus, for example, if I wanted to know how a maintenance man spends his time on a certain job, and for some reason I could not take direct measurements, I might (1) ask a sample of the maintenance men to complete an "activities" checklist and (2) interview another, independent sample as to the nature of their job activities. If the results from these two approaches agree, one can be reasonably sure that he has reliable data, which is always a reason for rejoicing.

Prediction of Maintainability

Towne gave an interesting paper on maintenance prediction techniques. His time-synthesis technique reminds me of earlier industrial engineering standard times systems which have enjoyed considerable success in industry. I would urge that any experimental work carried out in this area should give special attention to selection of the samples of subjects. They should be representative of U.S. Navy maintenance men and not college sophomores. I hope, further, that our dedication to the time criterion will not cause us to neglect the total job context, including such factors as job enrichment. To paraphrase what someone said, "design a system that fools can maintain and only fools will want to maintain it." We don't want, or need, a repetition of the early job simplification work of Taylor and the Gilbreths. (Towne did not imply this; I just want to be sure that we keep it in mind if and when we restructure maintenance jobs.)

Hsu presented an excellent assessment on prediction of maintainability. In addition to warning us about problems of additivity and sequence, I find myself in complete agreement with him on the limited usefulness of time, at least as currently measured, as a criterion. It is insensitive to design variables, downtime is contaminated with factors over which the maintenance man has no control, etc. We must refine the traditional time measures if we have any hope of ever using them.

I must address Hsu's criticisms of techniques such as the RCA technique. It was fully realized when it was adopted that the technique had many imperfections; however, many felt that it was the best available, or even the only game in town. It is too bad that more effort has not been expended to correct its deficiencies.

Risk Assessment/Cost-Effectiveness

Orlansky for years has been in the forefront of those urging others in the human factors field to express their results in terms of risk assessment and cost-effectiveness. I can only urge that more of us heed his admonitions. Orlansky is also a proponent of the cross-discipline approach to human factors problems. Again, heed him--a wise man with much experience. The very complexity of the maintenance problem assures that no one engineering or scientific specialty will have the answer to more than a small piece of the problem. The cross-discipline approach breeds synergism. This area needs that.

Diagnostics

Inaba suggests that as equipment becomes more automatic, diagnosis will become more difficult. Certainly, unless we devote more thought and effort to the problem, Inaba is correct. Consider, for example, that with automatic equipment one source of information regarding malfunctions (the operator) is completely missing. Man-machine "intimacy" is greatly reduced.

Inaba's prediction was verified by Rouse who found that when automatic equipment failed, the maintenance men had no idea why. Under such conditions, they often make matters worse by doing counterproductive things. It suggests

to me that in the era of automaticity the diagnostician (perhaps a person different than he who fixes it) will have to have a better understanding of the system than has often been the case in the past.

I have gathered evidence which convinces me that in many jobs approximately 70 percent of the maintenance man's job is spent trying to determine precisely what is wrong with the equipment that he is attempting to maintain. This requires a sensitivity to subtle cues, a familiarity with software (the maintenance man of the future almost certainly will have to be a software expert), and an ability to integrate information from a number of sources. The locus of this activity in Figure 2 is "brain and spinal cord." And, let's face it, that is the one box of the five shown in Figure 2 about whose functioning we know least.

The diagnostic part of the maintenance man's job is more like that of the veterinarian than the physician. In neither the case of the maintenance man nor the veterinarian do the patients say much to the individuals who are trying to help them. As human factors specialists, is it not our responsibility to see that equipment communicates its problems more effectively to the maintenance man, preferably before irreversible damage or complete breakdown have occurred?

This latter requirement, essentially that of preventative maintenance (recall my earlier statement that, on the average, corrective maintenance costs three times as much as preventative maintenance), means that <u>patterns</u> of symptoms will become more important than individual symptoms and that <u>rates</u> at which things are changing, or derivative information, will be very helpful. This means also that the feedback provided by the equipment must be more and more specific--"operating or not operating" is no longer specific enough. Rather, "I'm operating but notice that my temperature is rising rapidly and my bearings are beginning to chatter. Better check my oil!" (Parenthetically, I observe that we have been rather sloppy with respect to our demands for feedback. In learning situations, for example, we often assume that as long as the person is getting some kind of feedback [a letter grade, for example] that everything is O.K. We must insist that the feedback be specific and be intimately related to the nature of the action we expect from the person. A yellow caution light should be just one of a number of feedback communications from equipment to operator or maintenance man.)

The things just described will enable the maintenance expert to make a <u>prediction</u> as to what will happen and when it will happen if certain actions are not taken. Sometimes these patterns of symptoms will be so complex that it is unreasonable to expect the average line maintenance man to make the correct diagnosis. (That he often doesn't is evidenced by the fact that nearly 50 percent of the time commercial aircraft maintainers remove a nonfaulty part because of the faulty diagnosis [Burrows - personal communication]. I need not remind you what the actions of removal and replacement themselves eventually can do to reliability.) Just as there are expert diagnosticians in medicine, so should there be in maintenance. I understand that at least one robotics company has a team of expert diagnosticians in the home office who can be called toll-free at any time

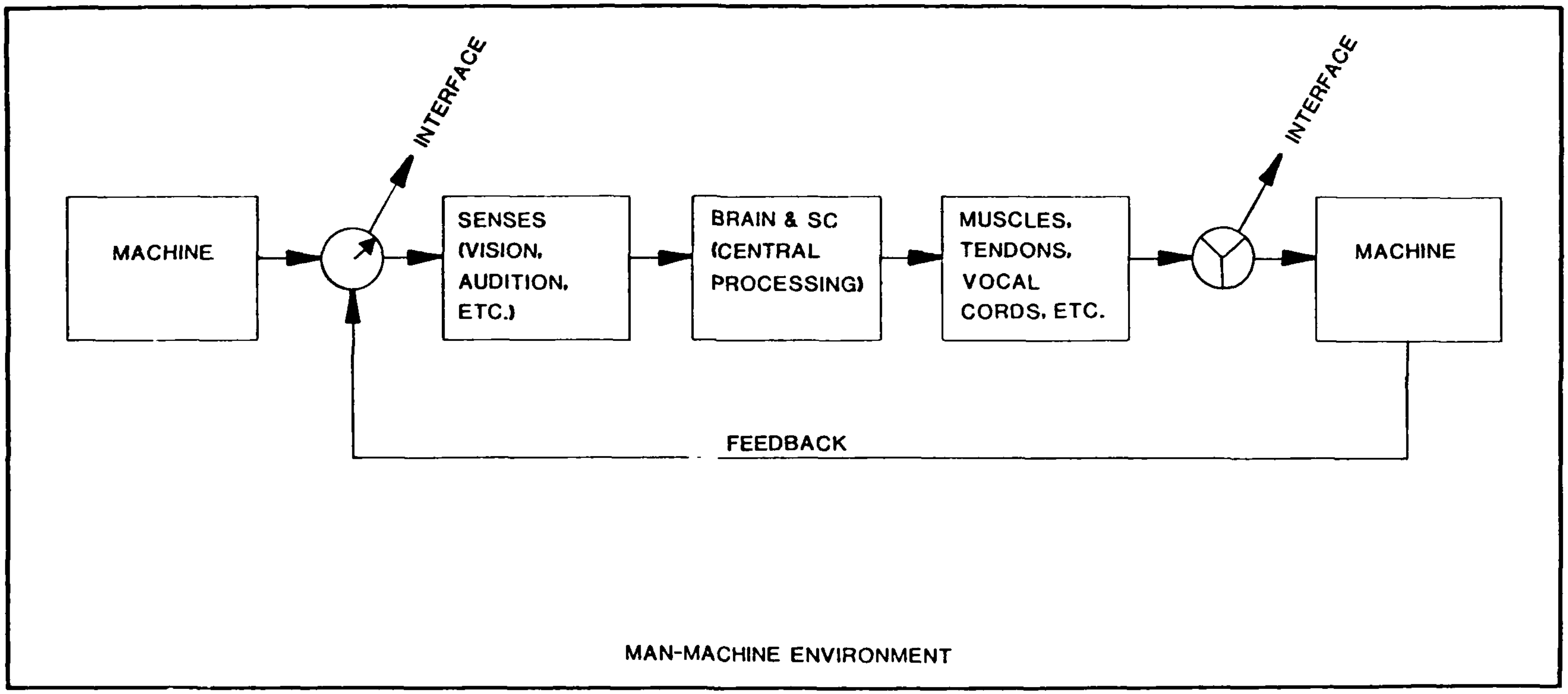


Figure 2. A man-machine model (note "interfaces").

regarding the meaning of certain symptoms that the robot is evincing. Might not the Navy designate specialists in diagnostics who would be available to assist the line maintenance men?

All of this leads one to propose a sort of "strategy for curing sick systems." Its steps appear to run somewhat along the following lines:

1. initial maintenance requirements established during systems analysis

2. proper functions allocation

3. interface design (otherwise we will have a garbage in--garbage out situation)

4. selection of people with proper aptitudes and attitudes

5. training with emphasis on troubleshooting (as it is now, most maintenance men troubleshoot in a haphazard manner or in some favorite way that they have picked up somewhere but which may be quite inappropriate)

6. constant sharpening of diagnostic skills (one study showed that skilled maintenance men sample with a purpose while the unskilled sample and then try to decide what to do)

7. proper manual and job-aids design

8. reasonable environmental conditions

9. machines that communicate their ills to man

10. strong, active management support of the maintenance program.

What Is a Maintenance Error?

Although I have heard frequent reference to the term at this conference, I cannot help but observe that even in this sophisticated group, no one has defined it! I would think that a clear definition of error, plus a classification of types and number of errors, would be most useful. For example, if a maintenance job takes four times as long to perform as it should, is this an error? Is an error that is discovered and corrected before the job is completed an error?

If systematic errors are discovered in acts such as calibration, they can be corrected by the application of constants. Random errors can be corrected to some extent by redundancy.

As Singleton has suggested, one looks for consistency in such matters, not simply rationality. It is clear that a program directed toward reduction of errors in maintenance must consider the same behavioral parameters (admittedly from a somewhat different point of view) as reduction of errors in operation--clear, unequivocal inputs that facilitate central nervous system processing plus unambiguous means for making the necessary motor responses. Appropriate feedback attesting to the success or failure of directed actions is a necessity (see Figure 2).

Models

Good models can lead to good theories and, as is often said, there is nothing as practical as a good theory. We have seen many good examples of modeling at this conference; perhaps we will see theories emerging from some of them in the near future, or at least adoption and/or elaboration of existing theories to accommodate maintenance issues.

It is encouraging to see the support that ONR is giving this area. I'm not familiar with Towne's work on troubleshooting strategies but I do hope that it takes account of not only the particular characteristics of the U.S. Navy maintenance population but also the differences within that population. I would be astonished, for example, if any single troubleshooting strategy proved to be best for everyone.

I find Sheridan's discussion on internal/external models useful in situations such as this. You may recall that Sheridan suggests that the greater the differences between the internal model and the corresponding external model, the more elaborate will be the transfer functions between the two. It would appear profitable to make these as similar as possible, but how to do it? Once maintenance personnel are selected, it would appear that training would be the primary resource available to assure veridicality between the internal and external models. ("Training," in this context, includes the materials used in instruction, as well as on-the-job manuals, etc.). The external model is determined by design features and is clearly within the province of human factors engineering. The model validates the close interrelationship between training and human factors engineering that Professor Rouse supported with his remarks.

Design for effective maintenance must follow the systems development model. The results of interviews that I conducted with systems engineers and design engineers convince me that most (70-90 percent) of the major design decisions (the "drivers," as they are often termed) are made by the end of the conceptual stage. The implications of this are clear: we will never be in a position to optimize the external model ("optimize" here means maximum correspondence between internal and external models) until we are able to specify design requirements at the initial stages of equipment and systems development. We have not been able to do this; perhaps this is the reason that the engineers seem more and more to be going to ATE and BITE. (Topmiller and I have elaborated on something developed by Crawford and Altman that appears in HEGED. It might help a bit in this regard [see Figure 3].)

Finally, if the model doesn't fit carefully collected human performance data, change the model!

A Strategy for Curing Ills

All of the above leads me to propose a strategy for curing maintenance ills. What might be some of the components of that strategy?

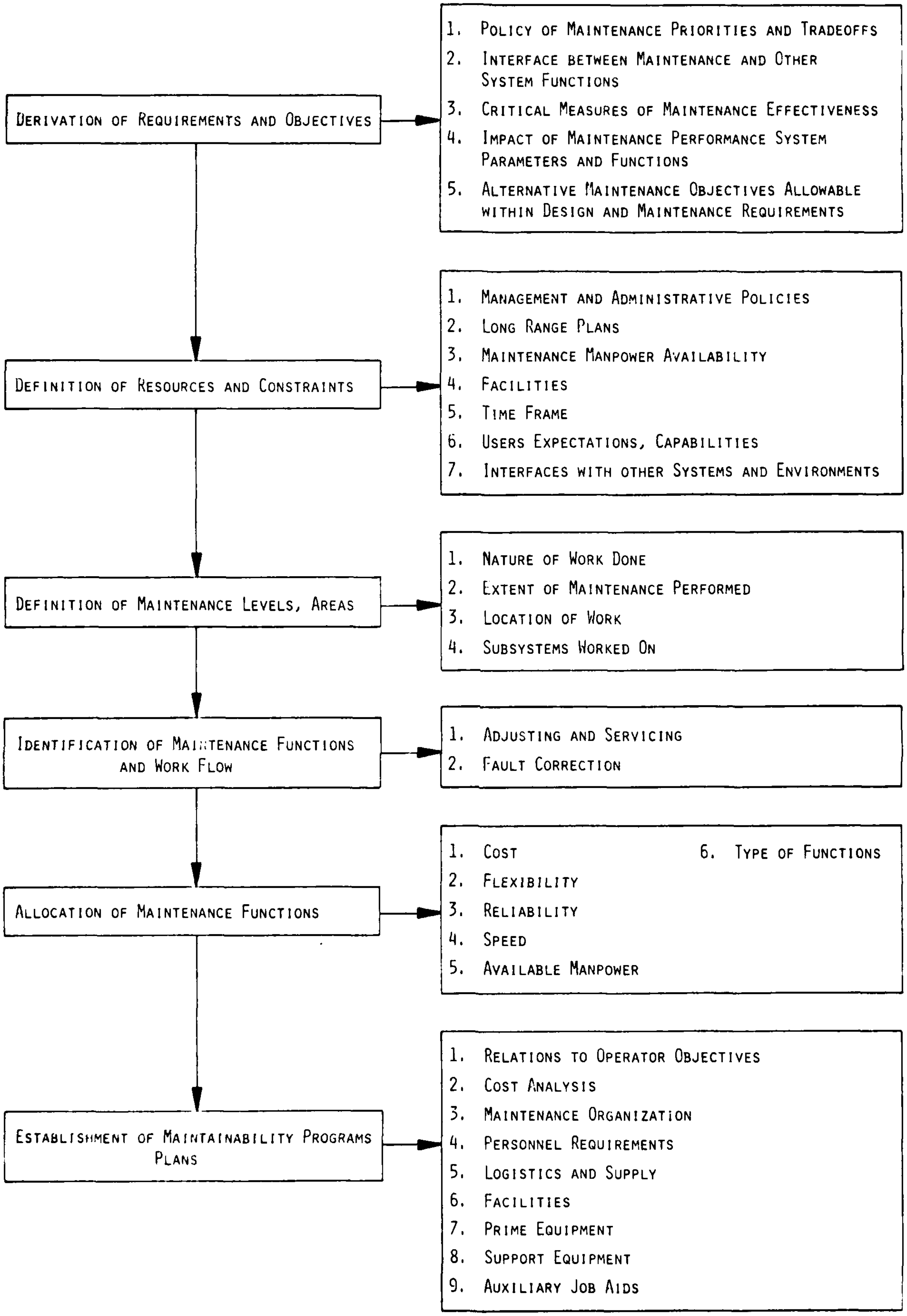


Figure 3. Steps in idealized phasing of maintainability design. (Source: Topmiller and Christensen, Maintainability Assessment and Design for Nuclear Power. Adapted from Crawford and Altman in Van Cott and Kinkade, pp. 588.)

Model/Theory Development

You might feel that the human factors problems associated with maintenance are so pressing that we don't have time to develop models and theories. I suggest that we don't have time not to do so. We have been struggling along in a piecemeal fashion in this area for at least 25 years and, frankly, we aren't much closer to a solution than we were a generation ago. Let us at least take what is relevant and available from existing theories of human performance and begin the arduous task of relating these to the development of some overall "theory of human performance in maintenance." We may be surprised at what we already know--but it does need integration.

Systems Analysis

Our strategy must include a systems analysis whose products help us as early as possible in the developmental cycle to identify maintenance functions.

Functions Allocation

Once these functions are identified, we must allocate them to man, to machines, and to combinations of men and machines. Task analyses, appropriately employed, can be of considerable help here.

Interface Design

We know a lot about interface design that we could apply to the man-machine interaction but in the past we seem to have slighted the maintenance man in favor of the operator. We cannot, for example, expect valid diagnostics without valid and appropriate inputs into the central nervous system of the maintenance man.

Workplace Design

Virtually no attention has been given to the design of workplaces for maintenance, both within the system and at the bench level. I recall a visit to the RCA plant in Anderson, Indiana, where most of the wiring and plumbing on the machine tools had been removed from the bowels of the equipment and made more accessible to the maintenance man. The effects on morale and maintenance costs were impressive. This leads to the next component of our strategy.

Environmental Considerations

Pianka reminds us of the importance of environmental factors. We have considerable knowledge regarding the effects of individual stressors--temperature, illumination, etc. Why aren't we as concerned about those instances where the maintenance man is involved, as those where the operators are involved?

Manuals and Other JPAs

This is an area about which we know quite a bit and have even applied some of that knowledge. Yet I still see manuals with readability indexes at the 10th-12th grade level, illustrations poorly integrated with text, etc.

Machines Monitor Men

It was my mentor's fond hope that, since men are such poor monitors, we would someday be clever enough to design systems in which machines would monitor men--"don't do this to me, it will cause a malfunction;" "you are unduly stressing me." Through the use of interlocks, caution lights, record-keeping, surrogates, and the like, we have made some progress toward Paul Fitts' goal but have a long way to go. Communication between equipment and its maintainers needs much more work. Let's design hardware so that it will tell us when and where it hurts so that we can help it before it suffers a breakdown. Outpatient care is much less expensive than hospitalization.

Selection and Training

We contend that we are "systems-oriented" in our approach to the solution of problems. Thus, we must include selection and training considerations in our strategy. We must develop means for facilitating the examination of the multitude of tradeoffs involved in the selection x training x human engineering interaction. We have developed specialists among the functional areas of maintenance (electronic, mechanical, etc.); perhaps we should consider the development of specialists within functional areas (experts in diagnostics, for example).

Organizational Considerations

If nothing else, a firm's table of organization tells you what functions that firm considers significant. All of you know industrial firms that have a vice-president for operations. How many of you know of firms that have a vice-president for maintenance? I know a few--one is United Airlines, the firm that supplied the supporting data to which I referred earlier.

For far too long the maintenance man has felt, and usually with justification, that he and his contributions were secondary to others in the system. One survey disclosed that maintenance men feel (1) that designers intentionally, or at least through lack of attention, build in irritation factors for maintenance men, (2) that management largely ignores maintenance men, and (3) that computers are little more than expensive nuisances. Look in the mirror--what kind of support is your organization giving the maintenance man? In this technological age, I can see us gradually dispensing with operators for many functions; I cannot see us dispensing with maintenance men.

The procuring organization (SPO?) has a responsibility to develop a genuine capability on its side. Otherwise adequate assessment of the offeror's product from the standpoint of maintainability is impossible.

Final Element of Our Strategy

As I review the elements of our strategy for curing maintenance ills, one item pervades my thoughts--yes, we need better models and theory, but, as Orlansky and Inaba pointed out, there is an enormous amount of information already available that we're not applying. As Orlansky said, "Let us document our successes and sell them in terms of readiness, manpower and cost-effectiveness." And let us also heed Inaba's admonition to the effect

that we must be prepared to pay for maintainability in our systems. But let's be sure that when management is ready to listen we have our product well-defined so we can offer a meaningful, well-integrated package.

And, finally, let's open up the lines of communication, not only with management, but also with the maintenance men themselves. Theisen and his associates have given us a taste of the good things that can result from field records. Let's encourage means for increasing the effectiveness of communications between operators and maintenance men. When you take your automobile into the garage for repair, you can help the mechanic a great deal by describing the symptoms that you have observed. Yet I have had pilots tell me that there is no sense in writing a detailed description of observations of incipient or actual malfunctions because "they can't fix it anyway." What a sad commentary on the quality of communications between operators and maintenance men.

(As I am writing this, a fellow worker, John Howard, put an advertisement in front of me in which the headline states, "With Digital's Remote Diagnosis, we know what's wrong with your computer before we get there." That's what I'm talking about!)

Criteria

No one would question the need for adequate criteria in the area of design for maintenance. What do we mean by "adequate criteria"? As a minimum, the criteria must be reliable, valid, and sensitive. The most commonly used criteria in the past have been time-related: MTBF, MTTR, etc. These measures may be reasonably reliable, perhaps valid (at least for some purposes), but their sensitivity to human factors parameters must be questioned. As a minimum, it would appear that time measures need to be broken down into their components since the gross time figures appear to be overwhelmed by matters over which the individual maintenance man has little or no control.

Errors constitute good criteria but there are difficulties here also. They are difficult to record, their definition often causes difficulty, self-incriminating errors are seldom reported, and, as stated previously, occasionally malfunctions that never happened are reported.

Other criteria, then, are cost and unnecessary replacement of parts. One can imagine the difficulties associated with obtaining reliable, valid, sensitive information on the human factors aspects of such criteria.

Lacking good field criteria for assessing the effectiveness of training, we have adopted the time-honored procedure of using school achievement and performance on the job. Orlansky reminds us that a positive correlation between these two variables has yet to be established. We must remind ourselves, however, that this does not mean that the training program is of no value. The lack of correlation could be a reflection of (1) the lack of reliable field criteria, (2) the lack of reliable classroom criteria, (3) the lack of any positive relationship even with reliable criteria, or (4) all of the above.

Orlansky has shown the way to begin to develop improved criteria with his plea for more and better quantification and exploitation of what is already available. The accident and mishap data base that Schmitt and his associates are developing looks promising.

Concluding Remarks

The goal is clear; the way is not. All of us know what we would like to achieve; namely, the means for developing a maintainability program that, when implemented, would contribute maximally to the effectiveness of that system--effectiveness to be determined by measurement in terms of the criteria specified by the systems manager and systems engineer.

LT McBride is proceeding on a broad front to satisfy these requirements and that is necessary. Excellent work has been reported here; it is his very difficult and important job to see how these pieces fit together. The very process of attempting to fit them together will disclose those points at which gaps in the program exist and/or where emphasis may have been misplaced. I know that I speak for everyone here when I say that I sincerely hope that these proceedings have helped him a bit with that difficult assignment.

References

Berliner, C., Angel, D., & Shearer, J. W. Behaviors, measures and instruments for performance evaluation in simulated environments. Symposium and Workshop on the Quantification of Human Performance, Albuquerque, NM, August 1964.

Swain, A. D., & Guttman, H. E. Handbook of human reliability analysis with emphasis on nuclear power plant applications (NUREG/CR-1278). Washington, D.C.: U.S. Nuclear Regulatory Commission, October 1980.

APPENDIX A

APPENDIX A

Twenty-four people responded to the survey conducted at the Design-for-Maintainers Conference, held in Pensacola Beach, Florida, 9-11 March 1982. Seventeen were psychologists, five were engineers, and two were maintenance people.

There is a total of 376 years of human factors experience, with a mean of about 15 years. One hundred and thirty-seven are in Design (mean about 8), seventy-five in Training (mean about 6), thirteen in Selection (mean about 3), one hundred and thirty in Application (mean about 9) and ninety-one in Technical Development (mean about 8).

1. Assuming a "triad model," what relative emphases are presently applied to the following elements? Rate your choices on the ten-point scales provided, such that they add to ten.[1]

	Mean ($\bar{x}$)	Range Low	Range High
Design	4.5	2	9
Training	3.7	1	7
Selection	3.1	1	6

2. What is your perception of our historical emphasis in each of these three areas? ($\Sigma = 10$)

	Mean ($\bar{x}$)	Range Low	Range High
Design	3.5	1	8
Training	4.3	1	9
Selection	3.1	1	7

3. What is the ideal investment of emphasis? ($\Sigma = 10$)

	Mean ($\bar{x}$)	Range Low	Range High
Design	5.8	3.5	8
Training	3.3	1	8
Selection	2.5	1	8

4. What future investments emphasis do you predict will actually be made in these three areas? ($\Sigma = 10$)

	Mean ($\bar{x}$)	Range Low	Range High
Design	4.7	2	8
Training	3.8	2	9
Selection	2.6	1	9

---

1 The rationale for the forced cumulative scheme is that, emphasis, defined here as money, is assumed finite and inelastic. If some investment, therefore, is divided among three independent recipients, the sum must persist in adding to the original, NIF and introductory questionnaire theory notwithstanding.

5. With respect to reliability and maintainability, give your opinion as to the percentage of emphasis typically given to each approach during the design phase of equipment evolution? (Σ = 100%)

	Mean ($\bar{x}$)	Range Low	Range High
Reliability	71.5	50	90
Maintainability	28.5	10	50

6. For the future, where do you predict the emphasis will actually be placed? (Σ = 100%)

	Mean ($\bar{x}$)	Range Low	Range High
Reliability	59.1	40	80
Maintainability	40.0	20	60

7. What is your opinion of current Built-in-Test (BIT) technology?

extremely effective: 0
very effective: 2
somewhat effective: 15
ineffective: 6
very ineffective: 1

8. What is your opinion of BIT's future?

extremely effective: 3
very effective: 11
somewhat effective: 8
ineffective: 1
very ineffective: 1

9. In which of the following should we invest ourselves? (Σ = 100%)

Diagnostics ≈ 60%
Remove/Repair/Replace ≈ 40%

10. Rate on the ten-point scale your feelings regarding the importance of Robotics for maintenance in the future. $x \doteq 5$

APPENDIX B

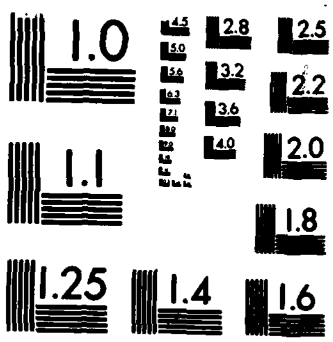
AD-A160 934 PROCEEDINGS OF A CONFERENCE ON A COMPREHENSIVE TECHNICAL REVIEW OF HUMAN (U) NAVAL AIR DEVELOPMENT CENTER WARMINSTER PA D K MCBRIDE ET AL 11 MAR 82 3/3

UNCLASSIFIED SBI-AD-F630 624 F/G 5/5 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AGENDA

DESIGN FOR MAINTAINERS CONFERENCE

9-11 March 1982
Holiday Inn Convention Center by the Sea
Pensacola Beach, Florida

TUESDAY, 9 MARCH

0830 - 0900	Registration
0900 - 0930	A Human Factors Design-for-Maintainers Technology Development Program D. McBride, J. Lambert (Naval Air Development Center/Eagle Technology, Inc.)
0930 - 0945	An Overview of ONR Human Factors Research Programs G. Malecki (Office of Naval Research)
0945 - 1030	Developing Solutions to Problems K. Inaba, F. Fuchs (XYZYX Information Corporation)
1030 - 1100	Coffee Break
1100 - 1200	Developing Solutions to Problems (Cont.)
1200 - 1330	LUNCH
1330 - 1400	The Performance of Maintenance Technicians on the Job J. Orlansky, J. String (Institute for Defense Analyses)
1400 - 1445	Derivation of Maintainability Design Guidelines: An Experimental Approach C. Theisen, S. Hsu (Essex Corporation)
1445 - 1515	Coffee Break
1515 - 1600	A Survey of Methodological Issues in Maintainability Research S. Hsu, C. Theisen (Essex Corporation)
1600 - 1615	Evaluating the Effectiveness of Maintenance Training by Using Currently Available Maintenance Data J. String, J. Orlansky (Institute for Defense Analyses)
1830 - 1930	Social Hour - hors d'oeuvres, limited open bar

WEDNESDAY, 10 MARCH

0800 - 0830	Coffee
0830 - 0930	Diagnostic Psychological Issues and Maintenance Design Features D. Towne (Behavioral Technology Laboratories, University of Southern California)
0930 - 1000	Human Factors, System Safety, and Aviation Maintenance M. Pianka (Naval Air Test Center)
1000 - 1030	Coffee Break
1030 - 1100	Design for Effective Maintenance (DEM) J. Schmitt, L. Lamb, J. Mocharnuk (Harris Corporation)
1100 - 1200	Design, Implementation, and Evaluation of Approaches to Improving Maintenance Through Training W. Rouse (Georgia Institute of Technology)
1200 - 1330	LUNCH
1330 - 1415	Cost-Effectiveness of Maintenance Simulators for Military Training J. Orlansky, J. String (Institute for Defense Analyses)
1415 - 1445	Biodynamic Modeling of the Maintainer E. Winkler, J. Miller (McDonnell-Douglas Corporation)
1445 - 1515	Coffee Break
1515 - 1545	Using Design for Maintainer Technology: Lessons Learned T. Jones, D. Mahar (Pacific Missile Test Center)
1545 - 1615	Comparing Engineering Psychology and Industrial Engineering Approaches to Logistic Problems R. Keesee (University of Louisville)
1615 - 1645	A Critical Review J. Christensen (General Physics Corporation)

THURSDAY, 11 MARCH (closed session)

0800 - 0830	Coffee
0830 - 1000	Review Panel
1000 - 1030	Coffee Break
1030 - 1200	Review Panel (Cont.)
1200 - 1330	LUNCH
1330 - 1500	Review Panel (Cont.)
1500 - 1530	Coffee Break
1530 -	Review Panel (Cont.)

APPENDIX C

Conference On Design-for-Maintainers
9-11 March 1982

ATTENDEE LIST

Dr. William B. Askren
AFHRL/LRL
Wright-Patterson AFB, OH 45433
Commercial (513) 255-3771
Autovon 785-3771

Ms. Diana Barry
Rowland & Co.
6961 Hanging Moss Rd.
Orlando, FL 32807
Commercial (305) 677-6951

Dr. Julien Christensen
General Physics Corporation
1010 Woodman Drive, Suite 240
Dayton, OH 45432
Commercial (513) 254-6707

Dr. William H. Crooks
Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, CA 91367
Commercial (213) 884-7470

LCDR Larry M. Dean
CNO (OP-115E)
Washington, DC 20350
Commercial (202) 694-4970
Autovon 224-4970

Dr. Floyd Glenn
Analytics
2500 Maryland Rd.
Willow Grove, PA 19090
Commercial (215) 657-4100

Mr. John F. Hayes
US Army Research Institute
ATTN: PERI-II (Mr. Hayes)
5001 Eisenhower Ave.
Alexandria, VA 22333
Commercial (202) 274-8695
Autovon 284-8695

Ms. Laura Hitchcock
Essex Corporation, Suite 200
65 West Street Road
Warminster, PA 18974
Commercial (215) 674-8710

Mr. Wayne Hostetter
Allen Corp. of America
3751 Maguire Blvd.
Suite 270
Orlando, FL 32803
Commercial (305) 896-9300

* Dr. Shang Hwa Hsu
Essex Corporation
65 West Street Road
Suite 200
Warminster, PA 18974

Dr. Kay Inaba
XYZYX Information Corp.
21116 Vanowen Street
Canoga Park, CA 91303
Commercial (213) 883-8200

Mr. Paul Kaster
Eagle Technology, Inc.
2300 South 9th St., Suite 400
Arlington, VA 22204
Commercial (703) 979-8300

* Dr. Robin Keesee
Speed Scientific School
University of Louisville
Louisville, KY 40208

Mr. Harland Kidwell
Singer Link Flight Simulation Division
2224 Bay Area Blvd.
Houston, TX 77058
Commercial (713) 488-5510

* See Distribution List for Current Address

Mr. Larry C. Lamb
Harris Corporation
Gov't Electronics Systems Div.
P.O. Box 37
Melbourne, FL 32901
Commercial (305) 729-7127

* Dr. Joseph V. Lambert
Eagle Technology, Inc.
320 West Street Road
Warminster, PA 18974

* LT Dennis McBride
Naval Air Development Center
Code 6021
Warminster, PA 18974
Commercial (215) 441-2561
Autovon 441-2561

Dr. L. Bruce McDonald
McDonald & Associates, Inc.
988 Woodcock Rd.
Suite 136
Orlando, FL 32803
Commercial (305) 896-8539

Mr. Dale E. Mahar
Pacific Missile Test Center
Human Factors Engineering Branch
Code 1226
Point Mugu, CA 93042
Commercial (805) 982-8981
Autovon 351-8981

Mr. Gerald S. Malecki
Code 442 EP
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217
Commercial (202) 696-4741
Autovon 226-4741

* LCDR T. Mitchell
Crew Systems Division
Naval Air Systems Command
Washington, DC 20361

Dr. John B. Mocharnuk
Harris Corporation
Government Electronics Systems Div.
P.O. Box 37
Melbourne, FL 32901
Commercial (305) 727-6131

Dr. Tony Modrick
Honeywell, Inc.
MN 17-2314
2600 Ridgway Parkway
Minneapolis, MN 55440
Commercial (612) 378-5016

Mrs. Louida D. Murray
Eagle Technology, Inc.
320 West Street Road
Warminster, PA 18974
Commercial (215) 672-6250

Mr. Gregory J. Opetosky
Lund Consulting, Inc.
1903 E. Main St.
P.O. Box 315
Mohegan Lake, NY 10547
Commercial (914) 528-8709

Dr. Jesse Orlansky
Institute for Defense Analyses
1801 N. Beauregard Street
Alexandria, VA 22311
Commercial (703) 845-2293

Mr. William J. Phillips
Computer Sciences Corporation
6565 Arlington Blvd.
Falls Church, VA 22046
Commercial (703) 237-2000

LCDR M. J. Pianka
Code SY 50
SETD
Naval Air Test Center
Patuxent River, MD 20670
Commercial (301) 863-4146
Autovon 356-4146

* See Distribution List for Current Address

Mr. Joseph Pontecorvo
Federal Aviation Administration
Aircraft Maintenance Division
800 Indepedence Avenue, SW
Washington, DC 20591
Commercial (202) 426-3546
Autovon 426-3546 (FTS)

Mr. William Rizzo
Naval Training Equipment Center
Code N-712
Orlando, FL 32813
Commercial (305) 646-5130
Autovon 791-5130

Dr. William B. Rouse
Center For Man-Machine Systems Research
Georgia Institute of Technology
Atlanta, GA 30332
Commercial (404) 894-3996

Mr. Curt Sandler
NAVAIRSYSCOM
AIR-5313D
Washington, DC 20361
Commercial (202) 692-7486/7

Dr. John C. Schmitt
Harris Corporation
Gov't Electronics Systems Div.
P.O. Box 37
Melbourne, FL 32901
Commercial (305) 729-7127

Dr. C. J. Theisen, Jr.
Essex Corporation
65 West Street Road
Suite C-200
Warminster, PA 18974
Commercial (215) 674-8710

Mr. Guice Tinsley
Federal Aviation Administration
800 Independence Ave.
Washington, DC 20591
Commercial (202) 426-9472

Dr. Douglas M. Towne
Behavioral Technology Laboratories
1845 South Elena Avenue
Fourth Floor
Redondo Beach, CA 90277
Commercial (213) 540-3654

Mr. Martin A. Traub
Appli-Mation, Inc.
6955 Hanging Moss Rd.
Orlando, FL 32807
Commercial (305) 678-6955

Mr. Edward R. Winkler
McDonnell Douglas Corporation
Dept E423, Bldg 271C/1/MS168
P.O. Box 516
St. Louis, MO 63166
Commercial (314) 233-7096

Mr. T. J. Wong
Douglas Aircraft Co.
MS 35-36
3855 Lakewood Blvd.
Long Beach, CA 90846
(213) 593-8641

APPENDIX D

Design-for-Maintainers Conference
Conference Proceedings
Distribution List

Dr. Earl Alluisi
Chief Scientist
HQ, AFHRL
Brooks AFB, TX 78235
'.Commercial (512) 536-3605

Mr. P. J. Andrews
Code 03416
Naval Sea Systems Command
Room 880, Crystal Plaza 6
Washington, DC 20362
'.AV 222-9760/1/2/4
'.Commercial (202) 692-9760/1/2/4

CDR James H. Ashburn
Naval Aerospace Medical Research Lab
Pensacola, FL 32508

Dr. William Askren
AFHRL/LRL
Wright-Patterson AFB, OH 45433
'.AV 785-3771
'.Commercial (513) 255-3771

Ms. Diana Barry
Rowland & Co.
6961 Hanging Moss Rd.
Orlando, FL 32807
Commercial (305) 677-6951

Dr. Robert E. Blanchard
M-8 Monticello Street
Del Mar, CA 92014

Lt. Col. Joseph Birt
AFHRL-LR
Wright-Patterson AFB, OH 45433
'.AV 785-3713
'.Commercial (513) 255-3713

Dr. Richard Bromberger
Naval Material Command (MAT 08D4)
Crystal Plaza 5
Washington, DC 20360
'.AV 222-2164
'.Commercial (202) 692-2164

Mr. Gerald Chaikin
Human Engin. Lab. Detachment
DRXHE-MI
US Army Missile Command
Redstone Arsenal, AL 35898
'.AV 746-2048
'.Commercial (205) 876-2048

CAPT. Paul R. Chatelier
OUSDR&E
Room 3B129 Pentagon
Washington, DC 20301
'.AV 225-9777
'.Commercial (202) 695-9777

Dr. Julien Christensen
General Physics Corp.
1010 Woodman Ave.
Dayton, OH 45432
'.Commercial (513) 254-6707

Dr. William H. Crooks
Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, CA 91367
Commercial (213) 884-7470

LT Thomas N. Crosby
Naval Training Equipment Center
Code N712
Orlando, FL 32813
'.Commercial (305) 646-5130

CDR Mike Curran
Code 270
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22204
'.AV 220-4713
'.Commercial (202) 696-4713

LCDR Larry M. Dean
Chief of Naval Operations (OP-115)
Washington, DC 20350
'.AV 224-4970
'.Commercial (202) 694-4970

CAPT Derr, USN
Chief Naval Operations
OP 514, Room 4D371
Navy Department
The Pentagon
Washington, DC 20350

LT Micheline Eyraud, MSC
US Naval Safety Center
Code 1212
Naval Air Station
Norfolk, VA 23511
(804) 44-7926

Mr. John Fargher
Light Armored Vehicle Directorate
Development Center, MCDEC
Quantico, VA 22134
AV 278-2092/5
Commercial (703) 640-2092/5

Mr. Gerald J. Fox
Head, Life Sciences
M.S. B25-35
Grumman Aerospace Corp.
Bethpage, NY 11714

LCDR Larry Frank
Code N-712
Naval Training Equipment Center
Orlando, FL 32813
Commercial (305) 646-5130

Mr. Clarence Fry
U.S. Army Human Eng. Lab.
ATTN: DRXHE-AD
Aberdeen Proving Ground, MD 21005
Commercial (301) 278-2822

CDR Joseph Funaro
Naval Air Development Center
Code 602
Warminster, PA 18974
AV 441-2411
Commercial (215) 441-2411

Dr. Richard F. Gabriel
Douglas Aircraft Co.
C1-E80, Code 35-36
3855 Lakewood Blvd.
Long Beach, CA 90846
Commercial (213) 593-8642

CAPT. Thomas Gallagher
Code 703
Naval Air Development Center
Warminster, PA 18974
AV 441-2191
Commercial (215) 441-2191

CDR Richard Gibson, Head
Aerospace Psychology Office (Med 3C13)
Bureau of Medicine and Surgery
Naval Department
Washington, DC 20372

Dr. Floyd Glenn
Analytics
2500 Maryland Rd.
Willow Grove, PA 19090
Commercial (215) 657-4100

CDR David M. Graves
ODASN (M)
The Pentagon RM 5D800
Washington, DC 20350
AV 227-2427
Commercial (202) 697-2427

Dr. Douglas Harris
President and Principal Scientist
Anacapa Sciences, Inc.
P.O. Drawer Q
Santa Barbara, CA 93102

Ms. Sandra Hart
NASA Ames Research Center
ATTN: MS 239-3
Moffett Field, CA 94035
Commercial (415) 965-6072

Ms. Christine Hartel
U.S. Army Research Institute
PERI-SM (Hartel)
5001 Eisenhower Ave.
Alexandria, VA 22333

Mr. John F. Hayes
US Army Research Institute
ATTN: PERI-II (Mr. Hayes)
5001 Eisenhower Ave.
Alexandria, VA 22333
Commercial (202) 274-8695
Autovon 284-8695

LCDR Wade Helm
Code 6021
Naval Air Development Center
Warminster, PA 18974
*AV 441-2561
*Commercial (215) 441-2561

Ms. Laura Hitchcock
Essex Corporation, Suite 200
65 West Street Road
Warminster, PA 18974
Commercial (215) 674-8710

Dr. Lloyd Hitchcock
Federal Aviation Administration
ACT-230
Atlantic City, NJ 08405
*Commercial (609) 641-8200 x3378/3379

Dr. Richard Hornick
Head, HF & Systems Safety
Systems Division
Hughes Ground Systems
Bldg. 606, MS K214
Fullerton, CA 92634

Mr. Wayne Hostetter
Allen Corp. of America
3751 Maguire Blvd.
Suite 270
Orlando, FL 32803
Commercial (305) 896-9300

Dr. Shang Hwa Hsu
XYZYX Information Corp.
21116 Vanowen Street
Canoga Park, CA 91303
Commercial (213) 883-8200

CDR Charles W. Hutchins
Naval Postgraduate School
Code 55
Monterey, CA 93940

Dr. Kay Inaba
XYZYX Information Corp.
21116 Vanowen Street
Canoga Park, CA 91303
Commercial (213) 883-8200

Dr. Edgar M. Johnson
U.S. Army Research Institute
5001 Eisenhower Ave.
Alexandria, VA 22333
*AV 284-8921
*Commercial (703) 274-8921

Mr. Jimmie H. Johnson
Essex Corp.
333 N. Fairfax St.
Alexandria, VA 22314

Dr. Richard Johnson
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333
*AV 284-8943
*Commercial (202) 274-8943

CDR Tom Jones
Naval Air Systems Command
Code 340F
Washington, DC 20361
*(202) 692-7418/9

Mr. Paul Kaster
Eagle Technology, Inc.
2300 South 9th St., Suite 400
Arlington, VA 22204
*Commercial (703) 979-8300

Dr. Milton Katz
U.S. Army Institute
5001 Eisenhower Ave.
Alexandria, VA 22333
*Commercial (703) 274-8622

Dr. Robin L. Keesee
U.S. Army Research Institute
ATTN: PERI-SM
5001 Eisenhower Ave.
Alexandria, VA 22333
*AV 284-8905
*(202) 274-8905

Dr. R. Kennedy
Canyon Research/Suite 227
1040 Woodcock Rd.
Orlando, FL 32803
*Commercial (305) 894-5090

Mr. Harland Kidwell
Singer Link Flight Simulation Division
2224 Bay Area Blvd.
Houston, TX 77058
Commercial (713) 488-5510

Dr. Judy Komacki
EES/EDC
Georgia Institute of Tech.
O'Keefe Blvd.
Atlanta, GA 30332
Commercial (404) 894-3844

Mr. Larry C. Lamb
Harris Corporation
Gov't Electronics Systems Div.
P.O. Box 37
Melbourne, FL 32901
Commercial (305) 729-7127

Dr. Joseph V. Lambert
6340 East Valley Green Rd.
Flourtown, PA 19031
Commercial (215) 233-5671

CDR Norman Lane
Naval Training Equipment Center
Code N-7A
Orlando, FL 32813
Commercial (305) 646-5317/5964

Mr. William Lane
Naval Training Equipment Center
Code N-71
Orlando, FL 32813
AV 791-5692
Commercial (305) 646-5692

Mr. Warren Lewis
Code 8231
Naval Ocean Sys. Center
San Diego, CA 92152
AV 933-7372
Commercial (714) 225-7372

LT Michael Lilenthal
Pacific Missile Test Center
Code 1226
Point Mugu, CA 93042

Mr. Paul Linton
Naval Air Development Center
Code 6021
Warminster, PA 18974
AV 441-2561
Commercial (215) 441-2561

Ms. Linda Lund
Lund Consulting
1903 E. Main St.
Box 315
Mohegan Lake, NY 10547
Commercial (914) 528-8709

LT Dennis McBride (51)
Chief, Human Factors Psych. Div.
Naval Aerospace Med. Rsch. Lab.
NAS Pensacola, FL 32507

Dr. L. Bruce McDonald
McDonald & Associates, Inc.
988 Woodcock Rd.
Suite 136
Orlando, FL 32803
Commercial (305) 896-8539

Dr. James McGrath
NPRDC, Code 302
San Diego, CA 92152
AV 933-6617
Commercial (714) 225-6617

Mr. Dale E. Mahar
Pacific Missile Test Center
Human Factors Engineering Branch
Code 1226
Point Mugu, CA 93042
Commercial (805) 982-8981
Autovon 351-8981

Mr. Gerald S. Malecki
Code 442 EP
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217
Commercial (202) 696-4741
Autovon 226-4741

RADM R. Martini, USN
Chief Naval Operations
OP51-Room 4E360
Navy Department
The Pentagon
Washington, DC 20350

Dr. David Meister
Navy Personnel R&D Center
San Diego, CA 92152
Commercial (714) 225-6617

Mr. Steve Merriman
Code 6022
Naval Air Development Center
Warminster, PA 18974
AV 441-2411/2891
Commercial (215) 441-2411/2891

Mr. J. Miller
Life Sciences
P.O. Box 516
McDonnell-Douglas
Astronautics Co.
St. Louis, MO 63166

LCDR T. Mitchell
Pacific Missile Test Center
Code 1226
Point Mugu, CA 93042
Commercial (805) 982-8981

Dr. John B. Mocharnuk
Harris Corporation
Government Electronics Systems Div.
P.O. Box 37
Melbourne, FL 32901
Commercial (305) 727-6131

Dr. Tony Modrick
Honeywell, Inc.
MN 17-2314
2600 Ridgway Parkway
Minneapolis, MN 55440
Commercial (612) 378-5016

Dr. Heber G. Moore
HDQ Naval Material Command
ATTN: MAT 08D4B
Washington, DC 20360
Commercial (202) 692-2646

Mr. Ross Morgan
Technical Director
HRL/LR
Wright-Patterson AFB, OH 45433

CDR William F. Moroney
SY 72
Naval Air Test Center
Patuxent River, MD 20670

Dr. Fred Muckler
Canyon Research Group, Inc.
2135 Hartford St.
San Diego, CA 92110
Commercial (213) 889-5072

Mr. W. G. Muller
Systems & Research Center
PO Box 312
2600 Ridgway Parkway
Stop MN 172307
Minneapolis, MN 55440
Commercial (612) 378-5086

Mr. Miles R. Murphy
Aviation Safety Research Office
NASA-Ames Research Center
M.S. 239-2
Moffett Field, CA 94035
Commercial (415) 965-5906

Mrs. Louida D. Murray
Eagle Technology, Inc.
320 West Street Road
Warminster, PA 18974
Commercial (215) 672-6250

LCDR Kevin Myette
Chief Naval Air Forces
Atlantic Staff
NAS
Norfolk, VA 23502

Mr. Gregory J. Opetosky
Lund Consulting, Inc.
1903 E. Main St.
P.O. Box 315
Mohegan Lake, NY 10547
Commercial (914) 528-8709

Dr. Jesse Orlansky
Institute for Defense Analyses
1801 N. Beauregard Street
Alexandria, VA 22311
Commercial (703) 845-2293

LCDR Jerry Owens
Naval Aerospace Medical Research Lab.
Pensacola, FL 32508

Mr. William J. Phillips
Computer Sciences Corporation
6565 Arlington Blvd.
Falls Church, VA 22046
Commercial (703) 237-2000

LCDR M. J. Pianka
Code SY 50
SETD
Naval Air Test Center
Patuxent River, MD 20670
Commercial (301) 863-4146
Autovon 356-4146

Mr. Joseph Pontecorvo
Federal Aviation Administration
Aircraft Maintenance Division
800 Indepedence Avenue, SW
Washington, DC 20591
Commercial (202) 426-3546
Autovon 426-3546 (FTS)

Mr. William Rizzo
Naval Training Equipment Center
Code N-712
Orlando, FL 32813
Commercial (305) 646-5130
Autovon 791-5130

Dr. William B. Rouse
Center For Man-Machine Systems Research
Georgia Institute of Technology
Atlanta, GA 30332
Commercial (404) 894-3996

Mr. Arnold Rubenstein
Code NAVMAT
08D/07255
Room 1044
Naval Material Command
Crystal Plaza 5
Washington, DC 20360

Mr. Curt Sandler
NAVAIRSYSCOM
AIR-5313D
Washington, DC 20361
Commercial (202) 692-7486/7

Dr. Richard Schiffler
ASD/ENECH
Wright-Patterson AFB, OH 45433
AV 785-5597
Commercial (513) 255-5597

Dr. Sam Schiflett
Aircrew Systems
SY 70E
Naval Air Test Center
Patuxent River, MD 20670
AV 356-4157
Commercial (301) 863-4157

Dr. John C. Schmitt
Harris Corporation
Gov't Electronics Systems Div.
P.O. Box 37
Melbourne, FL 32901
Commercial (305) 729-7127

Dr. Robert Smith, Jr.
Office of the Chief of Naval Operations
Code OP-987H
The Pentagon
Washington, DC 20350
AV 227-1219
Commercial (202) 697-1219

Mr. Joseph Stahl
Human Factors Project Engineer
Ballistic Missile Division
TRW Systems, Bldg. 526/620
P.O. Box 1310
San Bernardino, CA 92402

Dr. C. J. Theisen, Jr.
Essex Corporation
65 West Street Road
Suite C-200
Warminster, PA 18974
Commercial (215) 674-8710

Mr. Guice Tinsley
Federal Aviation Administration
800 Independence Ave.
Washington, DC 20591
Commercial (202) 426-9472

Dr. Martin A. Tolcott
Office of Naval Resrch.
800 N. Quincy St.
Arlington, VA 22217

Dr. Donald Topmiller
AFAMRL/HED
Wright-Patterson AFB, OH 45433

Dr. Douglas M. Towne
Behavioral Technology Laboratories
1845 South Elena Avenue
Fourth Floor
Redondo Beach, CA 90277
Commercial (213) 540-3654

Mr. Martin A. Traub
Appli-Mation, Inc.
6955 Hanging Moss Rd.
Orlando, FL 32807
Commercial (305) 678-6955

Mr. Marshall Whiteaker
HQ AFLC/LOEP
Wright-Patterson AFB, OH 45433

Mr. Edward R. Winkler
McDonnell Douglas Corporation
Dept E423, Bldg 271C/1/MS168
P.O. Box 516
St. Louis, MO 63166
Commercial (314) 233-7096

Mr. T. J. Wong
Douglas Aircraft Co.
MS 35-36
3855 Lakewood Blvd.
Long Beach, CA 90846
(213) 593-8641

END

FILMED

12-85

DTIC